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High Pressure Combustion Tube Studies of Medium and Light oil

By
SHAABAN EL-USTA

Submitted for the degree of Doctor of philosophy of the University of Bath

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JANUARY 1998

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Nomenclature

A	cross sectional area
O_2	oxygen
N_2	nitrogen
CO2	carbon dioxide
CO	carbon monoxide
H/C	hydrogen carbon ratio of the fuel
k	reaction rate constant
$\varnothing$	porosity
Sw	water saturation
So	oil saturation
Sg	gas saturation
Sorg	residual oil saturation with respect to gas
Sorw	residual oil saturation with respect to water
K	absolute permeability
m_c	mass of fuel burnt (kg)
Vg	volume of gas required to burn a unit mass of reservoir (sm^3/m^3)
x	hydrogen to carbon ratio H/C
r	CO/ CO+CO_2
ρ	fluid density (kg/m^3)
ρ_o	density of oil (kg/m^3)
ρ_s	formation grain density (kg/m^3)
To	initial temperature °k (equation 2.1)
Ao	constant (sec^{-1} atm^{-n})
Px	oxygen partial pressure (atm abs) equation 2.1
c_1	specific heat of oil-bearing formation (kcal /kg°C), eq 2.1
c_s	specific heat of the formation grains (kcal /kg°C)

H	heat of reaction kcal/kgO_2 equation 1.1
n	pressure exponent
Po_2	oxygen partial pressure equation 1.3
E	activation energy
y_{CO}	CO mole fraction in produced gases
y_{CO2}	CO_2 mole fraction in produced gases
y_{O2}	O_2 mole fraction in produced gases
AAV	air activated valve
AFR	air to fuel ratio
AOR	air to oil ratio
AOFMV	air operated fine meter valve
API	American Petroleum Institute
ARC	accelerated rate calorimetery
BOPD	barrel of oil per day
BPR	back pressure regulator
BV	ball valve
CMG	Computer modelling group
COSHH	control of substances hazardous to health
CPC	current to pneumatic converter
CAR	compressed air regulator
EOR	enhanced oil recovery
F	gas filter
GC	gas chromatograph
H/C	hydrogen carbon ratio
HPS	high pressure separator
HTO	high temperate oxidation
IOR	improved oil recovery
ISC	in-situ combustion
LMF1	mass flow control valve (on oxygen line)

LMF2	mass flow control valve (on nitrogen line)
LTO	low temperature oxidation
OOIP	original oil in place
PID	proportional integral derivative control
PG	pressure gauge
PPRV	pressure regulator valve
PRVG	gas pressure reducing valve
PRVL	liquid pressure reducing valve
PT	pressure transducer
SAGD	steam assisted gravity drainage
scf	standard cubic feet
STARS	Steam and Thermal additive Reservoir Simulator
STB	standard tank barrel
SV	soniliod valve
TC	thermocouple
W50	coarse grad of Buckland sand
W150	fine grad of Buckland sand
WAG	water alternating gas
WAR	water air ratio
WT	wet test meter

Abstract

A high pressure, fully automated combustion tube facility was modified and extensive commissioning trials conducted. A series of in situ combustion experiments was carried out on medium heavy Clair oil 19.8 API, at pressures from 50 to 100 bar, and using air injection fluxes between 20 and 75 m^3/m^2hr. All of the experiments achieved high temperature combustion. The combustion performance was significantly affected by the air flux. The highest combustion temperature achieved was 700°C at an air flux of 75 m3/m2hr. While at a lower air flux (20 m^3/m^2hr, the stable combustion temperature averaged 470°C. The combustion front velocity also showed a significant decrease with decreasing air flux. The use of a finer grade of sand resulted in higher combustion temperatures (600°C) compared to the case where the coarser sand was used, achieving only 450°C, at the same air flux. All of the medium Clair oil experiments achieved high oxygen utilisation levels during the stable combustion periods, and were accompanied by substantial levels of CO2 produced(up to 15%) in the production gas.

The in situ combustion of light oil was also investigated in two experiments. These were carried out using an Australian light oil (38.78 API) at 70 bar pressure. Both runs failed to achieve high temperature combustion due to lack of fuel. However, these experiments were successful in sustaining propagating stable temperature front at approximately 250°C. This process is considered to operate mainly in a low temperature oxidation mode. However, the use of a high air injection flux in the light oil experiments, gave a lower oxygen utilisation and a faster front velocity. An exploratory simulation study of the process gave a realistic measure of agreement regarding the peak temperature and front velocity.

CHAPTER ONE

INTRODUCTION

Introduction

While the demand for oil products continues to rise globally at one to two percent each year, conventional oil production is set to undergo a steady decline. Alternative energy sources are under development but they will not be available at significant levels in the near-term. The petroleum technologies currently in use only enable 30-35% of the original oil in place to be produced, leaving 65-70% in the ground. This aspect and the increase of stabilisation in the oil price in recent years has prompted the need to develop new technologies to recover a significant amount of the remaining oil from known accumulations .

In the early stage of oil production, the internal energy of the reservoir is large enough to enable the oil to be produced naturally. i.e. by depletion, until eventually the production rates become uneconomic. Then new technical developments of oil production are needed to be employed which have become known as Improved Oil Recovery (IOR). A special category of IOR is called Enhanced Oil Recovery(EOR) and this includes advanced reservoir processes which permit the recovery of a higher percentage of original oil in place than would have been possible by using only primary and secondary recovery methods. These processes include mainly immiscible/miscible gas injection, chemical flooding (surfactant or polymer), thermal recovery and almost any technique which is able to increase oil recovery, from 3-D seismic to horizontal wells and Microbial (MEOR) technique .

The increasing demand for crude oil is growing at the rate of 1.2 billion barrels per year, and the difficulty of discovering new reservoirs has increased awareness of the need for more advanced enhanced oil recovery (EOR) methods capable of economically producing the crude remaining in known reservoirs.

The in situ combustion technique is a thermal recovery process which can be a very effective technique for the recovery of both heavy and light oils from reservoirs already depleted by both primary and secondary recovery operations. Air injection can offer unique economic and technical opportunities for improved oil recovery in many candidate reservoirs. Air injection is an efficient oil recovery process because only a small amount of the in place oil is consumed while the rest is displaced, and eventually produced.

The in situ combustion (ISC) process benefits include the following mechanisms in the reservoir; excellent displacement, high thermal efficiency, mobilisation of heavy oil components, reservoir pressurisation, gas stripping and thermal upgrading of the reservoir oil. For air injection into high pressure deep light oil reservoirs, extra benefits to be achieved, include spontaneous ignition and complete oxygen utilisation.

The main objective of the present study was to investigate in situ combustion of both medium and light oil under high pressure conditions (up to 150 bar) using a fully automated combustion tube system.

The aim was to achieve a greater understanding of the mechanisms which govern the in situ combustion process, in terms of combustion front stability, displacement efficiency and fuel - flux requirements.

The results obtained from the experiments side provide a basis for the validation of a numerical simulation model of in situ combustion process at reservoir operating condition.

CHAPTER TWO

LITERATURE REVIEW

2.1 Primary Oil Recovery.

Initially the oil reservoir contains a mixture of water, oil and gas in the pore space of the reservoir rock. These fluids are under certain pressures caused by the hydrostatic pressure of the ground water. At high pressure, a large part of gas components are dissolved in the oil, with some free gas compressed to form a gas cap . Generally the reservoir energy can be classified into three types :-

- ***Water drive***
- ***Gas in solution drive***
- ***Gas cap***

At the beginning any one of these forces or combination of them will be strong enough to provide the driving force to move the oil into the production well ,where it is transported to the surface by the differential pressure between the formation and the well head pressure.When the reservoir pressure (reservoir energy) is depleted or becomes insufficient to force the oil to the surface, then some artificial method is required. Artificial methods include electrical submersible pumps, sucker rod pumps and gas lift techniques. When the reservoir pressure becomes insufficient to enable the oil to flow through the reservoir porous media, then secondary recovery is required to produce the remaining oil .

2.2 Secondary Oil Recovery

The lack of sufficient natural pressure drive in most reservoirs occurs relatively early during the production life and causes the oil recovery rate to become uneconomic. However, the oil recovery can be increased by using methods of artificial drive, e.g. water or gas injection .

These techniques have been called secondary recovery, because the injected fluid results in a second stage of incremental oil recovery which is additional to that which can be achieved by primary recovery alone.

The main purpose of secondary recovery technique is to maintain reservoir pressure, or to increase the differential pressure between the drainage reservoir pressure and the well pore flowing pressure. They can be used also to create a driving mechanism to push the oil towards the producing wells. No physical or chemical change occurs by applying these techniques . Secondary recovery methods include water flooding and gas injection or a combination of both .

2.2.1 Water flooding

Water flooding is the oldest assisted recovery method. This technique was first started in the US in 1913. This technique had become perhaps the major contributor to the oil recovery. The application of water flooding for secondary oil recovery leads to an improvement in the reservoir sweep efficiency, but in addition, it can be used to:

1 . Maintain the reservoir pressure.

2 . Disposal of brine produced with oil by injecting it into an underlying aquifer.

The advantages of water flooding.

1. In reservoirs containing a low GOR ,water injection is the most suitable method, because the low gas oil ratio would result in only small volumes of gas being available for gas reinjection.

2. In heterogeneous water-wet reservoirs, water is more efficient than gas due to the spontaneous imbibition of water, which does not occur with gas injection.

The limitation on using water flooding.

1. The water does not flush all of the oil from the pore spaces as it moves through the reservoir rock , primarily because water and oil do not mix causing 25 to 50% of the oil to be left behind in a form of small droplets held within the pores.

2. The advance of a water front generally bypasses significant portions of the reservoir due to unexpected formation geology, and because of its low viscosity, the mobility ratio will be high and this results in a low sweep efficiency in cases where the oil viscosity is higher.

2.2.2 Immiscible Gas Injection

Secondary recovery techniques including the injection of natural hydrocarbon gas have been employed since 1900(**Schumacher, 1980**). The injection of natural gas is used mainly to maintain reservoir pressure (above the bubble point). The gas can be injected into a gas cap, if one exists or directly in to the oil zone. When gas injection takes place in a reservoir with a gas cap, the injected gas helps to maintain the reservoir pressure, while some of the gas invades into the oil zone as stable front, driving the oil towards the production wells. However in a reservoir with out a gas-cap, the gas flows radially from the injection wells immiscibly driving the oil towards the production wells.

In general, the major problem with gas injection is its inefficiency due to the low viscosity of the gas which results in increased bypassing of the oil, In addition to that problem, the availability of the natural gas and the economical aspects always determine the application of this technique.

2.2.3 Combination of gas and water injection

Gas can be used in conjunction with water flooding, this method has been tested in the field by Continental oil in the US and Sonatrach in Algeria. This method is known as a WAG, or water alternating gas process. Gas injection is followed by alternating large slugs of water to stabilise the gas front and results in improving the displacement efficiency and is more economical in the gas.

Another method has been carried out by the Creole company in lake Maracaibo where gas is injected into the cap with water injection down dip. The water pushes the oil towards the production wells while the gas prevents the oil from pushing into the gas cap(**Latil,1980**).

2.3 Enhanced Oil Recovery

There are no universally acceptable definitions of secondary and tertiary recovery. EOR methods usually follow secondary recovery, but in an optional sense, some EOR application should be used preferably at very early stages particularly where there is an advantage to be gained from a higher oil saturation. The various techniques involve chemical, miscible and thermal flooding. There is also a fourth category gaining in importance called MEOR, which uses microbial techniques.

2.3.1 Chemical flooding

Chemical flooding involves introducing some chemical material into the water flood in order to create advantageous changes in viscosity, mobility, surface tension and wettability. In general, chemical flooding can be classified into three main types:-

Polymer flooding

This involves the addition of a thickening agent (polymer) to the injected water in order to increase its viscosity. There are two benefits to be gained from this method :

(a) increase in sweep efficiency by improving the mobility ratio.

(b) reduction in the amount of water injection required to reach the ultimate residual oil saturation (Srow).

(c) to block high permeability strikes within the reservoir, thereby improving the sweep efficiency.

In general , there are two types of polymer which can be used to increase the viscosity of the water:

polyacrylamaides; these are synthetically produced material obtained by polymerisation of long chain of hydrocarbon molecules. Polyacrylamaides can decrease the mobility of the injected water by decreasing its permeability to the reservoir rock.

Polysaccharides; these natural materials are produced by treating a cultured micro-organisms, which are then dried and mixed with the injection water to create a very high viscosity. This polymer decreases the mobility of injected water by decreasing its viscosity.

Alkaline flooding

This technique involves a caustic chemical such as sodium hydroxide(NaoH) or sodium silicate(NaSiO3) in order to reduce the interfacial tension between the injected fluid and the reservoir oil, thereby improving the sweep efficiency. Alkaline fluids can also be used to change the reservoir wettability. This process can usually be applied with crude oils containing sufficient quantities of organic acids, that will react with the alkaline chemical to produce surface active agents. It has proved to be a successful EOR technique, when conditions permit.

Surfactant flooding:-

Surfactants are surface active agents, which include detergents. They can reduce the interfacial tension between water and oil to very low levels and mobilise the residual oil so that the microscopic displacement efficiency is close to 100 percent.

2.3.2 Miscible Gas Injection Process

Hydrocarbon Miscible Flooding

One of the most important requirements for oil recovery in oil-wet reservoirs is to overcome the surface tension trapping forces which tend to bind the oil to the rock as a film. In water-wet reservoirs, surface tension forces act to create isolated drops of oil which can be bypassed by displacing water, or cause blocking of the pore throats. The main object of miscible hydrocarbon fluids is therefore to reduce or eliminate the interfacial tension forces between the oil and the driving fluid. Useful fluids if available are light refined hydrocarbons, condensed hydrocarbon gases (LPG) and alcohols.

CO_2 Miscible Flooding

Carbon dioxide miscible flooding involves the injection of CO_2 which, if the pressure in the reservoir is sufficiently high, dissolves in the oil. This causes a reduction in oil viscosity, as well as vaporising lighter components as propane and butane, and on further gas contact with oil, the heavier components will be transferred into the vapour phase. The combination of these effects results in high displacement efficiency (for a North Sea light crude, partial miscibility starts at 70 bar and full miscibility around 270 bar.)

The **main advantages** of using CO_2 are therefore:

- swells the oil and reduces its viscosity.
- significant miscibility (greater than 30 %) can be achieved at relatively low pressures in many reservoirs
- CO_2 is neither hazardous nor explosive.

The **main disadvantages** of using CO_2 are:-

- The low viscosity of CO_2 gas at low pressure results in early breakthrough to the producing well, drastically reducing the sweep efficiency.
- Miscibility reduces the viscosity, which can lead to fingering and premature breakthrough.
- Carbon dioxide forms highly corrosive carbonic acid with water. More expensive corrosion resistant metals are required. It is preferable for CO_2 to only dissolve in the oil phase.
- Very large volumes of CO_2 are needed to run the process(5 to10MSCF per barrel of stock tank oil). Unless there are suitable nearby natural CO_2 aquifers (as in the US), alternative sources, such as power stations flue gas are unlikely to be economic.

Inert Gas Miscible Flooding

Oil displacement using inert gases such as nitrogen, is possible in certain reservoirs at sufficiently high pressure(greater than 400 bar). The resulting miscibility effect is similar to that described for the CO_2 process .

2.3.3 Thermal recovery

Thermal recovery methods are classified into two types. Firstly, those one in which the heat is produced at the surface (hot fluid injection), and secondly, where the heat is created in the formation (in situ combustion).

Thermal methods have greatest application in the recovery of extremely viscous, low API gravity crudes, such tar sands, heavy oils and bitumen . The common factor in all thermal methods is the ability to significantly increase the temperature of the reservoir. This involves specific mechanisms which improve

both the displacement and sweep efficiency, leading to increased rates of oil production.

Heavy oil reservoirs which contain highly viscous crudes (10^3 to 10^6 cp) have little or practically no mobility; for these reservoirs therefore to attain practical flow rates, the oil viscosity must be reduced significantly by several orders of magnitude. The main processes to introduce heat into the reservoir are: hot water, steam and in-situ combustion.

In practice, thermal methods are very efficient, but they require heavy investment and more careful attention to operating procedures than more standard methods of oil recovery. However, any increase in the price of oil will make thermal methods more economic for a greater number of oil fields.(**Moore et al, 1997**).

Thermal EOR techniques

Steam stimulation, in this method which is also known as cyclic steam injection, steam soak or "huff and puff, steam is injected into the production well. Then the well is shut in for a period of time to allow the heat to soak into the reservoir strata near the well. After that the well is placed back on production. This increases reservoir temperature, results in thermal expansion of the reservoir fluids, causing compression of solution gas. The resulting increase in mobility of the heavy oil leads to an increase in productivity. However, the productivity of this technique generally falls off progressively with successive steam cycles. After as little as three or four cycles, the production becomes uneconomic.

Steam flooding, this involves the injection of steam into group of outlying wells while the oil is produced from adjacent wells.

The process involved in steam flooding are shown in Fig.(1-1) :

(a) ***Steam zone (zone A):-*** The most important mechanisms in this zone are steam distillation and steam displacement. The presence of the steam vapour phase in contact with the crude oil and hot water downstream, causes vaporisation of the light oil fractions which are displaced by the steam flow.

(b)-***Condensation zone (zone B&C):-*** this zone comprises two parts. The first is the solvent bank in which most of the light oil fractions condense upon contact with the cold matrix. The second one is the hot water bank which result from condensation of the steam.

(c)-***Oil bank (zone D):-*** this zone contains the oil which has been displaced by steam. The maximum oil saturation can is reached in this zone.

(d)-***Initial zone(zone E):-*** This zone has not been affected by heat and contains original oil at the initial oil saturation.

Hot water flooding

Hot water flooding is used occasionally to recover viscous oil. This method is suitable in reservoirs which require only mild heating. The sweep efficiency of the hot water flood is not as high as in other thermal recovery methods. However, hot water can be injected at the beginning of the recovery process, then converted to steam injection after adequate injectivity has been established. This technique has been employed in Western Missouri, where Steam injectivity was found to be increased after the injection a substantial volume of hot water(**Schumacher, 1980**).

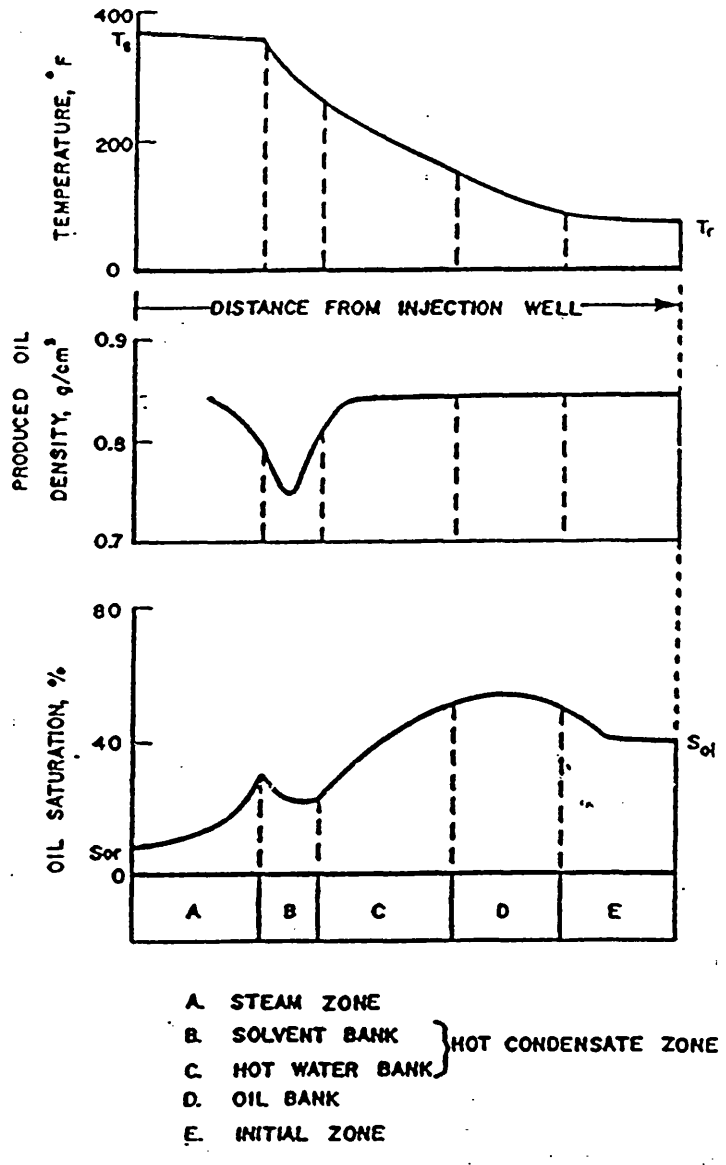

Fig. 2.1 Displacement of oil by steam injection. Burger 1985

2.4 In Situ Combustion Process

2.4.1 Introduction

The world's known reserves of conventional light oil are limited and it will be depleted in a relatively short time estimated to be 30 to 40 years, at the present consumption rates. The indications are that hydrocarbon production will gradually shift from the conventional crude supplies towards heavier oil, bitumen and residual light oils. Such a shift is already under way in the US, Canada, Russia and some other oil producing countries.

Heavy oil reservoirs are more suitable for the thermal recovery methods, but more researches have extended their application to cover residual light oils. Although the results for light oil recovery are very promising, more investigation needs to be undertaken to understand the mechanisms of light oil thermal process.

The in situ combustion process is a very complex process which involves chemical reaction and physical displacement processes coupled with simultaneous heat and mass transfer in a multiphase environment(**Kumar , 1991**). The process begins by injecting air into the reservoir, and then creating ignition near the injection well. The resulting combustion front moves away towards the production well. The heat generated by the combustion reactions is responsible for such processes as distillation and vaporisation, resulting in the reduction of crude oil viscosity. As a result of these processes, the heavier fraction of the oil remains behind, providing fuel through deposition on the reservoir rock. The lighter fractions of crude oil are carried downstream and condense in the cooler regions of the reservoir, forming an oil bank. The aim of an advanced process, such as in situ combustion, is to recover the trapped oil left behind by conventional reservoir production techniques. Apart from the very beneficial effect of temperature on reducing viscosity, particularly with medium and heavy crudes, there is another benefit of in-situ combustion which is the production of large quantities of CO_2. This is also advantageous in the recovery of lighter crudes, since CO_2 is miscible with oil at sufficiently high pressure.

This promotes swelling of oil, resulting in both viscosity reduction and displacement improvement. The major factor that influences the economics of the in-situ combustion process is the cost of air compression. COFCAW or Combination Of Forward Combustion And Water, results in very efficient heat transport from upstream heated zones to downstream zones. The air requirement is considerably reduced compared to dry combustion perhaps by as much as two thirds. This is achieved basically because the residence time for reactions (fuel deposition and combustion) is reduced, which increases the speed of the combustion front.

2.4.2 History of use

In situ combustion was first known in the early 1900's when under ground combustion was accidentally started when air injection was used to drive oil towards producing wells. Production increased and the heat effect in the reservoir was noted. The produced oil was co-produced with 10 to 15% carbon dioxide. Russians were the first to propose the concept of in-situ combustion for petroleum production. During 1932-34, the workers of GINI (state scientific research institute) carried out extensive laboratory studies on in-situ combustion method. This work was interrupted by the war, but it was resumed in 1964. In 1967, a field application of ISC was started at the Zybza containing heavy crude oil **(Baibakov,1989)** .

In US, the first test was performed by Magnolia petroleum in 1953. While the oldest full-scale in-situ combustion project was initiated in March 1958 at West Newport, California . This project was both a technical and economic success .

Since that early time, a great deal of attention and effort has been made in the study of the in-situ combustion process. These studies have involved both economic and technical aspects, as well as detailed combustion process mechanisms such as fuel deposition, air requirement, oxygen utilisation, combustion front velocity, reservoir characteristic effects, and combustion reaction parameters.

In spite of this intense study, many aspects of in situ combustion process are still not completely understood due to the complex nature of the process.

Turta, 1994, has reported at least 14 active commercial in- situ combustion projects world-wide in 1994 (six of them in US). In 1992 the Oil and Gas Journal reported that, the incremental daily oil production from ISC was about 32,000 barrels of oil per day (BOPD). In Romania the application of in-situ combustion processes started as early as 1963, and some reservoirs were designed to be produced entirely by this method. Four major heavy oil reservoirs there are currently being exploited by ISC, with a total daily oil production averaging 10,987 bbl/d. Oil recovery increases from 9% on previous production, to over 50% have been achieved by using this technique **(V. Machdon, 1994).**

Moore et al, (1997) , have reported 28 ISC projects carried out in Canada. The first was started in 1958 by Shell in the Athabasca region, the latest was started in 1994 by Amoco, at Wabasca - Alberta)

2.4.3 Screening of oil reservoirs for application of in-situ combustion

The application of in situ combustion depends on such factors as the depth of the oil reservoir, thickness of the pay zone(s), amount of oil in place, specific gravity of the crude and its fractional composition, geological types of the oil trap and the physical characteristics of the reservoir rocks **Baibakov, 1989.**

Some favourable parameters are as follows, although these are mainly based on heavy oil experience:

1. The thickness of the formation should be thicker than 10ft to avoid the possibility of excessive heat losses **(Burger and Soureau, 1972)** .

2. The porosity of the reservoir rock should be in the range of 12 to 43%. Porosity has a great effect on both the rate of advance of combustion front and the pressure that is required for the oxidant injection.

3. Viscous and low gravity crudes are best suited for in-situ combustion because they give enough fuel for combustion, but the oil should not be too viscous to avoid the formation plugging by the oil bank.

4. The permeability should preferably be at least 100 millidarcies, since if the permeability is too low , this will restrict the flow and may cause plugging of the formation if the crude oil is too viscous. On the other hand, if the permeability is too high ,this may result in premature gas breakthrough in to the producing wells **(Van P and Latil, 1980).** It is worth noting in this respect, that air injection has been made in deep light oil reservoirs where the permeability is only a few millidarcies.

5. The reservoir must have sufficient overburden and have sufficient extent of base and cap rocks so as to confine the injected air within the pay zone. Although no theoretical pressure limitation exists for air injection, the depth has an influence on the injection pressure, which accordingly affects the economics of the process. Depth also affects the fluid lifting cost **(Moore et al, 1997)**

2.5 In-Situ Combustion Methods

The principle of in-situ combustion is to achieve combustion within the pores of the reservoir rock, burning part of oil in place in order to improve the movement of the other part. Combustion is supported by the injection of air in to the reservoir. The heat generated during the combustion is sufficient to raise the rock to a high enough temperature to sustain self-propagation. The process of in-situ combustion can be presented in three main types, which are; forward in situ combustion, reverse in situ combustion and wet in-situ combustion.

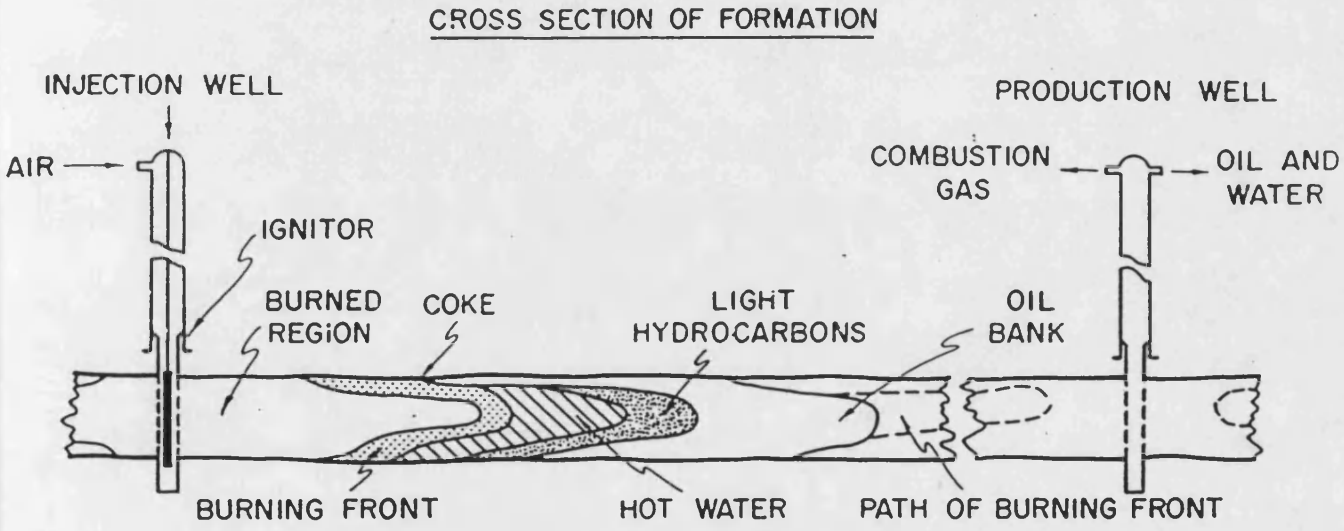

Fig. 1A.

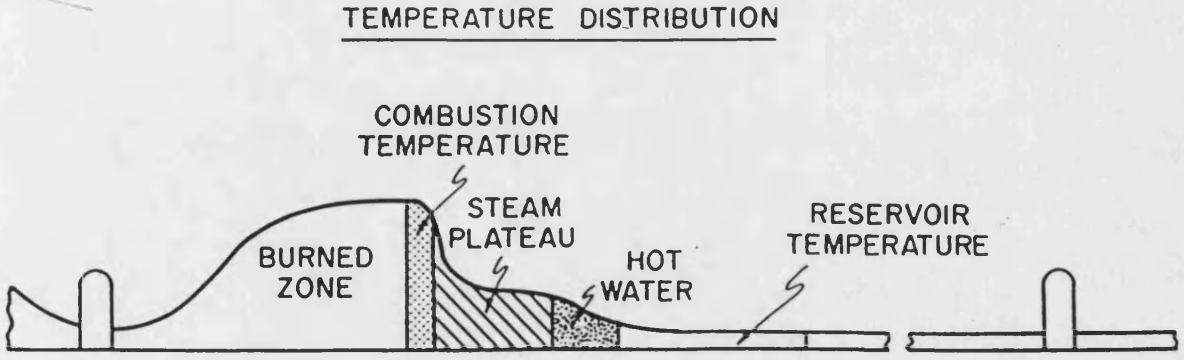

Fig 2.2 . Schematic diagram of in situ combustion process. (modified from Nelson and McNeil, 1961)

2.5.1 Dry forward in-situ combustion

In this process, the reservoir is ignited in the vicinity of an air injection well. The combustion front propagates toward the production well and continued injection of air maintains and drives the combustion front through the reservoir. Four principal zones can be defined as shown in Fig.(2-3):

ZONE-1: Combustion has already taken place and the formation in this zone is completely clean. The injected air is heated by the hot matrix and part of the combustion energy is recovered in this way.

ZONE-2: The combustion zone. Oxygen is consumed by combustion reactions. The temperature reached in this zone depends on the nature of the solids, liquids and gases present per formation volume.

ZONE-3: The coke formation zone. The heavy oil fractions which have been neither displaced nor vaporised undergo pyrolysis.

ZONE-4: Where the temperature has fallen sufficiently, there are no further significant chemical changes. This zone is swept by the combustion gases and displaced fluids.

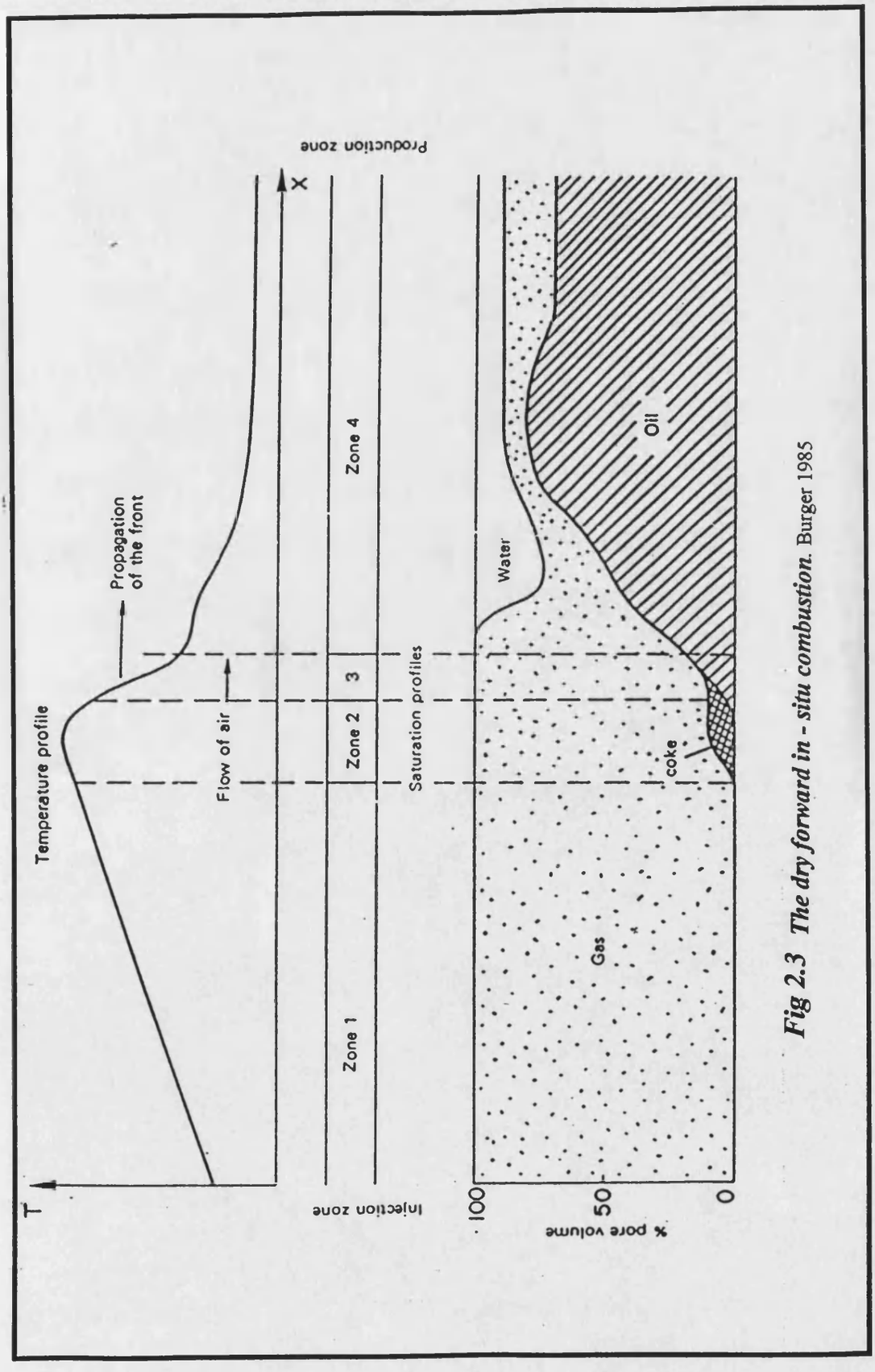

Fig 2.3 The dry forward in - situ combustion. Burger 1985

2.5.2 Reverse In- Situ Combustion.

The reverse in situ combustion process starts as forward combustion process, then after a while the air injection is switched off and changed, so that injection is through the production well. The combustion front will continue moving in the same direction and oil will be forced to go back through the combustion zone toward the previous injection well, which in fact now becomes a production well. This method allows the production of oil which is too viscous to flow under reservoir conditions.

The only limitation of this method is auto-ignition may take place, thus the whole process may change to forward combustion(**Burger, 1985**).

In general the process can be divided into four zones starting from the injection well as shown in Fig.(2-4).

ZONE-1: The formation is at original condition. However, it is being swept by air, and if the formation temperature and the oxidability of the oil are high, certain oxidation reactions may occur.

ZONE-2: The temperature increases in this zone by conduction from the hot zone downstream. The following phenomena occur; vaporisation of the formation water, distillation of the light fractions of the oil and cracking of certain hydrocarbons in the presence of oxygen. The liquid and vapour are displaced down stream, while the heavy fractions deposit "coke".

ZONE-3: The combustion zone where the temperature reaches its maximum.

ZONE-4: The unburned coke remains deposited on the matrix while the vapour and liquid phases flow downstream. If there are no heat losses, the downstream temperature would remain equal to that of the combustion front.

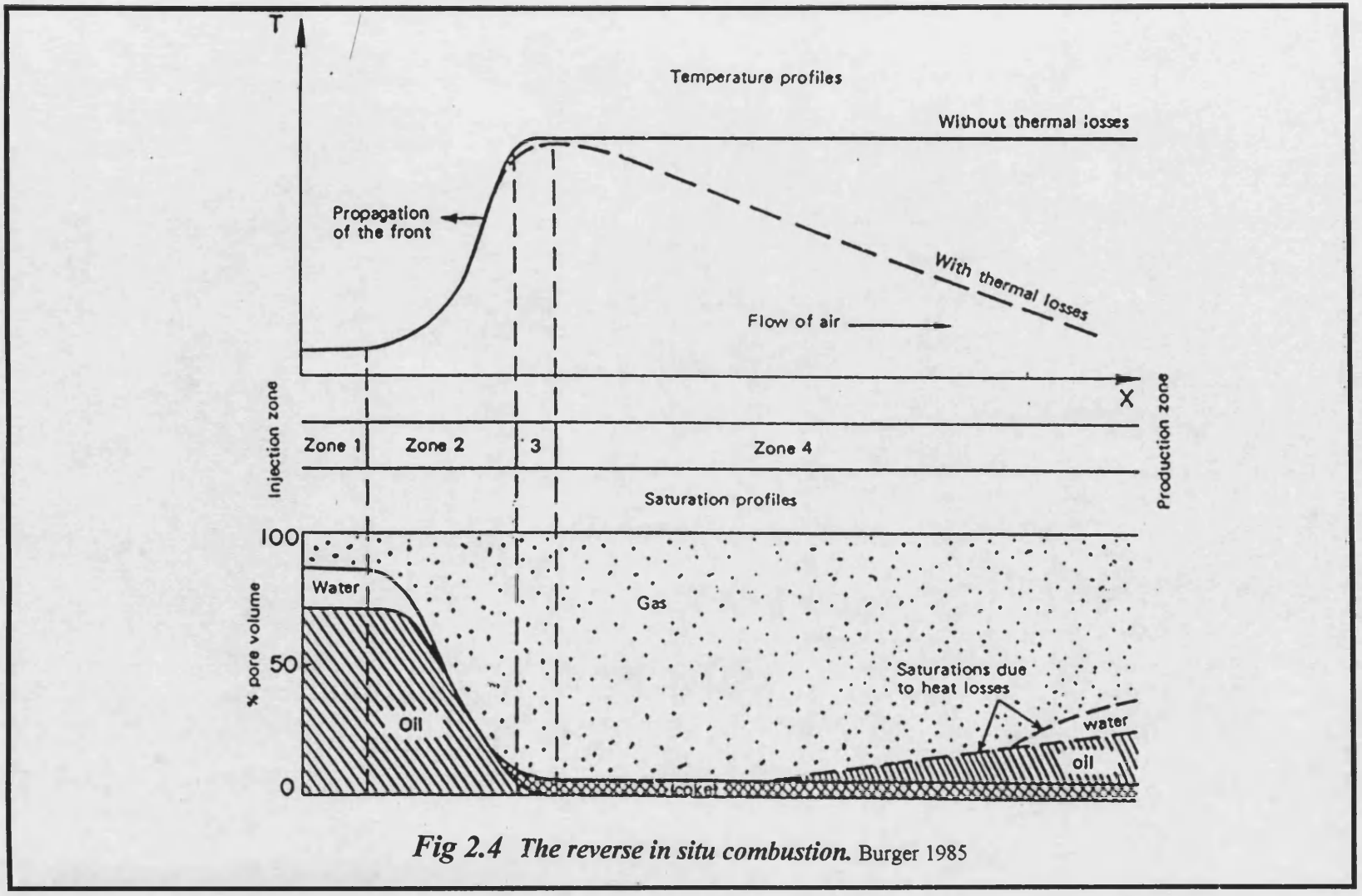

Fig 2.4 The reverse in situ combustion. Burger 1985

2.5.3 Wet In-Situ Combustion

The combination of forward combustion and water flooding (cofcaw) is called a wet combustion. Air and water are injected simultaneously or alternately after a small heat bank has been formed. When water in moderate amounts is injected simultaneously with air, it flashes into super heated steam a short distance from the injection well. The high thermal capacity of water can be used to cover the enthalpy remaining in the matrix behind the combustion front and transport it downstream. This process may be divided into five zones as shown in Fig.(2 -5).

ZONE-1: This zone has already been swept by the combustion front and contains little, or no hydrocarbon. The pores contain a liquid water saturation and the injected air.

ZONE-2: In this zone water is in vapour phase, and the pores are saturated with a mixture of injected air and steam. The injected water vaporisation front is at the boundary between zones1 and 2.

ZONE-3: The combustion zone.

ZONE-4: The vaporisation and condensation zone. The temperature in this zone is close to that of the vaporisation of water. Some light and intermediate oil fraction are vaporised and carried downstream. If the temperature is high enough low temperature oxidation (LTO) reactions may occur in this zone.

ZONE-5: This is a zone of high back pressure, due to the formation of a water bank preceded by an oil bank. Further downstream, the formation approaches its initial condition.

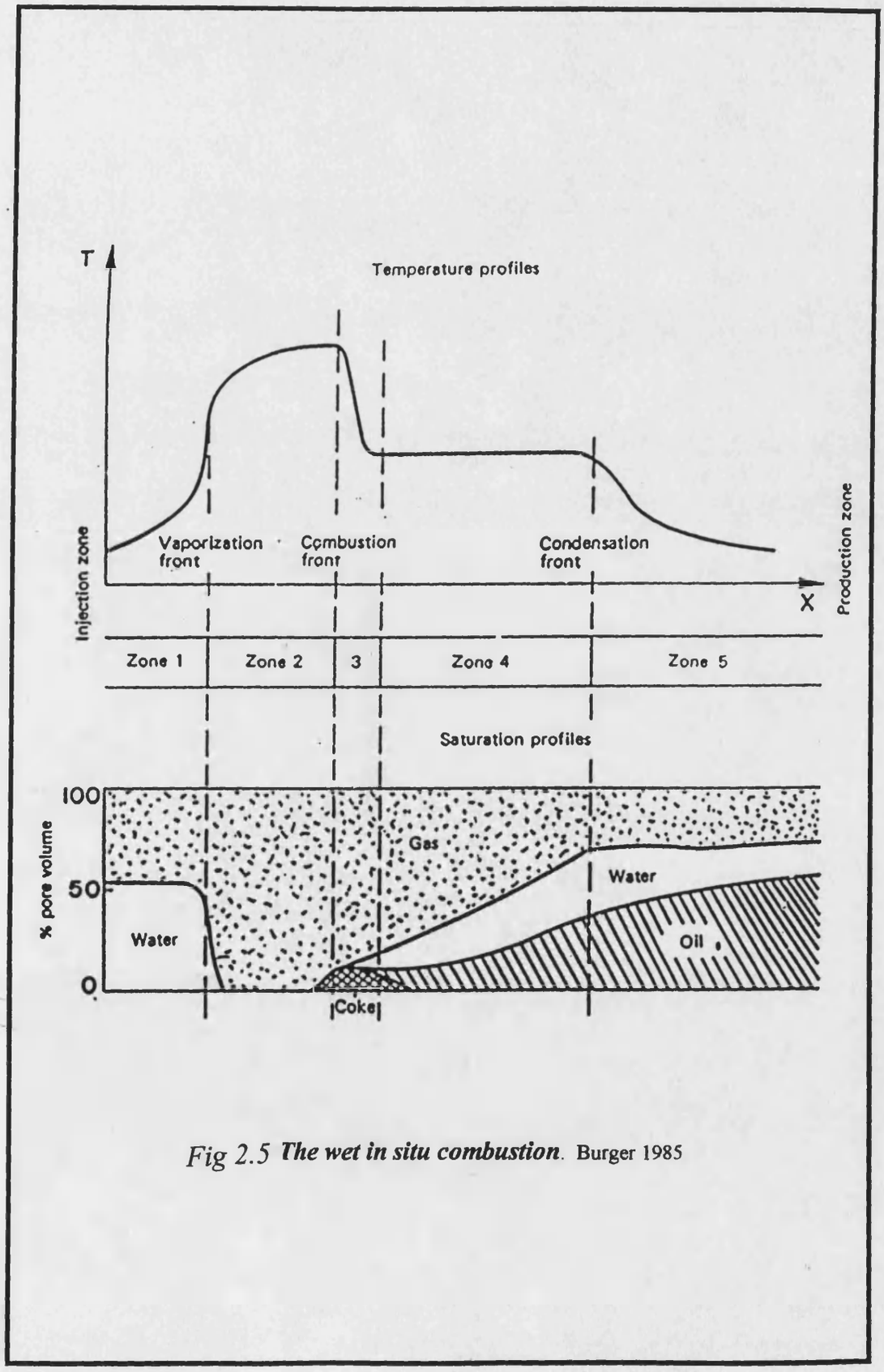

Fig 2.5 ***The wet in situ combustion***. Burger 1985

2.6 Discussion of technical parameters affecting in-situ combustion

2.6.1 Ignition

The ignition of the in-situ combustion can be defined as the moment at which the combustion starts. Ignition can be achieved either spontaneously or by some mechanical means. High powered electrical heaters are lowered into the air injection wells. This usually results in the formation of layer of coke around the wells, which is much more difficult to ignite than normal crude oil.

In forward combustion, when the injected air comes in contact with crude oil, oxidation of the crude oil takes place at reservoir temperature, which results in a slow rise in temperature. This rise in temperature increases the rate of oxidation, hence leading to a further rise in temperature. This process continues until the temperature of the oil has risen to the point at which spontaneous ignition takes place. Air preheating may be required to reduce the ignition time, from that achievable by low temperature oxidation alone and also to control the initial location of the ignition zone. According to **Tadema and Weijdema 1970** the ignition time can be estimated by the following formula:

$$t_i = \frac{\rho_1 c_1 T_o (1 + 2T_o/B)}{86400\ \phi S_o \rho_o H A_o P_x^n B/T_o} e^{B/T_o} \qquad (2.1)$$

Where:
t_i = ignition time (days)
ρ_1 = density of oil-bearing formation (kg/m^3)
c_1 = specific heat of oil-bearing formation (kcal/kg°C)

From the above equation, the ignition time mainly depends on the initial temperature and the specific heat of oil-bearing formation, hence ignition time can be reduced if preheated air was injected, although sever LTO reactions may affect the fuel availability and therefore the sustainability of combustion and this depends mainly on the composition of crude oil.

2.6.2 Air requirement

Generally, the air requirement in the in-situ combustion process is governed by the amount of fuel available for combustion. The combustion zone can move as fast as it depletes the deposited coke. If the amount of coke deposited is excessive, the rate of advance of the combustion zone will be slow and the air requirement therefore large.

The efficiency of oxygen utilisation depends on three parameters:-

(a) the carbon/hydrogen ratio (C/H) of the fuel or coke. When the C/H ratio of the crude oil is low, more air will be required since it requires more O_2 to oxidise hydrogen than to oxidise carbon.

(b) the amount of CO_2 produced since the amount required to produce CO_2 is twice that required to produce CO.

(c) the amount of O_2 which appears in the exhaust as produced gas.

Air to fuel requirement

The standard volume of gas required to burn a mass m_c of fuel is given by the equation(Burger, 1985):

$$Vg/m_c = \frac{b}{y_{o2}} \frac{2 - r + \frac{x}{2}}{12 + x} \qquad (2.2)$$

Where: b = coefficient (11.82 sm3/kg)

r = CO / (CO +CO_2).

b/yo_2 = 56.3 sm^3/kg when air is the injection gas

10 to 12 sm^3 of air are normally required to burn 1 kg of fuel in high temperature combustion reactions (Burger, 1985).

2.6.3 Fuel availability

Crude oils are often grouped into three categories, based on specific gravity of the oil, heavy oil (10-20 API), intermediate oil (20-30 API) and light oil which is greater than 30 API. Heavy oils consist mainly of high density naphthenes aromatics and heteroatoms, while light oil consists mainly of alkanes.(**Mamora, 1995**)

The principle of in-situ combustion is to achieve combustion within the pores of a hydrocarbon bearing reservoir by burning part of oil in place, and therefore improving the flow of the unburned part. The burning part of the oil in place can be defined as the fuel for the in-situ combustion process. The hot fluids flush out volatile and mobile substances from the path of combustion zone, leaving behind heavy residual hydrocarbon (coke). Fuel for the ISC process is strongly related to the sub-processes of vaporisation, distillation and thermal decomposition (cracking) of oil molecules. Generally, small hydrocarbon groups rich in hydrogen are broken off from the parent molecule producing the coke, which is left behind for combustion (**Lerner et al, 1985**).

Extensive laboratory work have been carried out to determine which factor affects the deposition of fuel during in-situ combustion.

Alexander et al 1962, summarised the factors affecting the fuel deposition as follows:

1. Initial oil saturation and rock quality Fig(5-a).
2. Residual oil saturation Fig (5-b).
3. Produced gas flux Fig(5-c).
4. C/H ratio Fig(5-d).
5. API gravity Fig(5-E).
6. Carbon residue Fig(5-F).
7. Crude viscosity Fig(5-G).
8. L.T.O. Fig(5-H).

Factors affecting the fuel availability of in-situ combustion

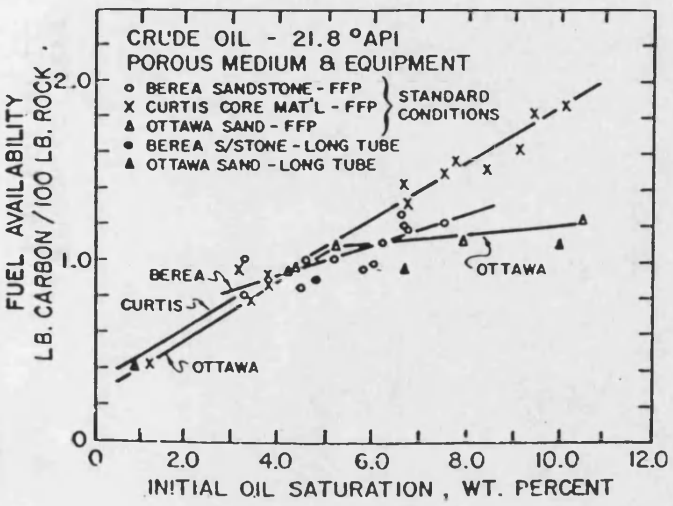

Fig (5-a) Effect of initial oil saturation on fuel availability. (after Alexander et al, 1962)

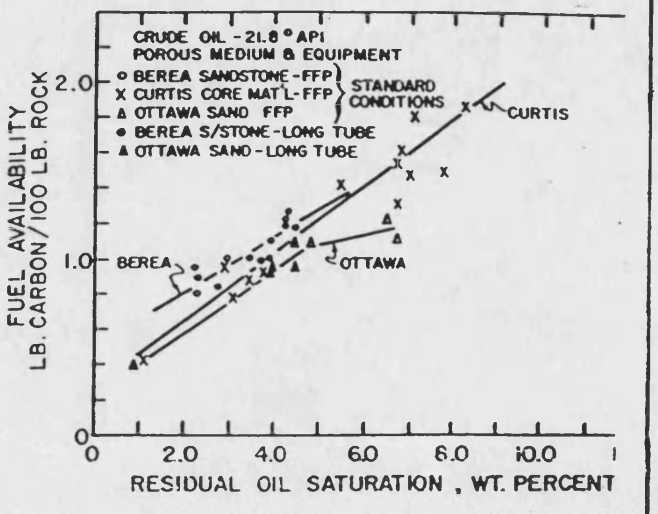

Fig (5-b) Effect of residual oil saturation on fuel availability (after Alexander et al, 1962)

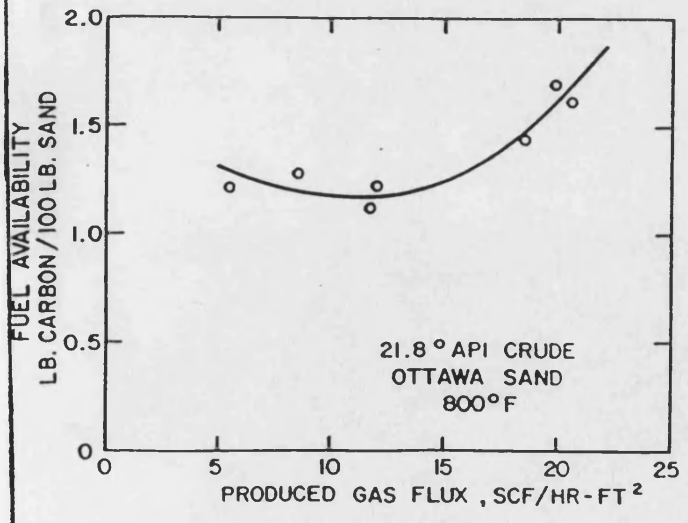

Fig (5-c) Effect of produced-gas flux on fuel availability. (after Alexander et al, 1962)

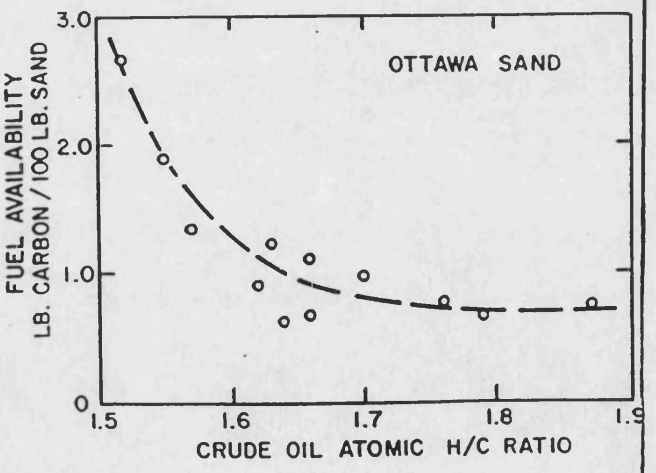

Fig (5-d) Correlation of fuel availability with crude-oil H/C ratio (after Alexander et al, 1962)

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Factors affecting the fuel availability of in-situ combustion

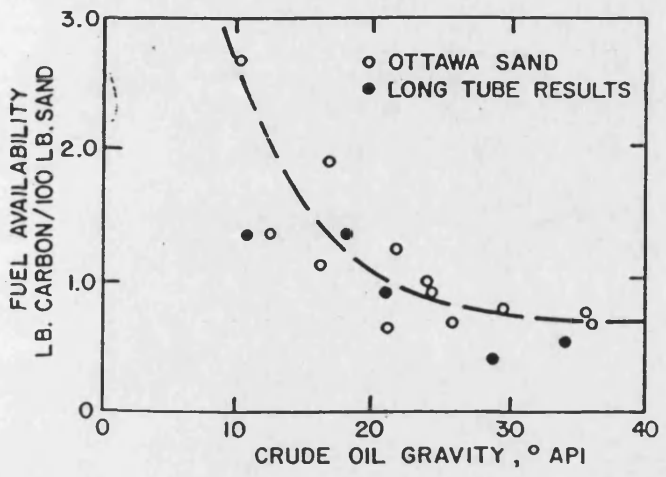


Fig (5-E) Correlation of fuel availability with crude-oil gravity.
(after Alexander et al, 1962)

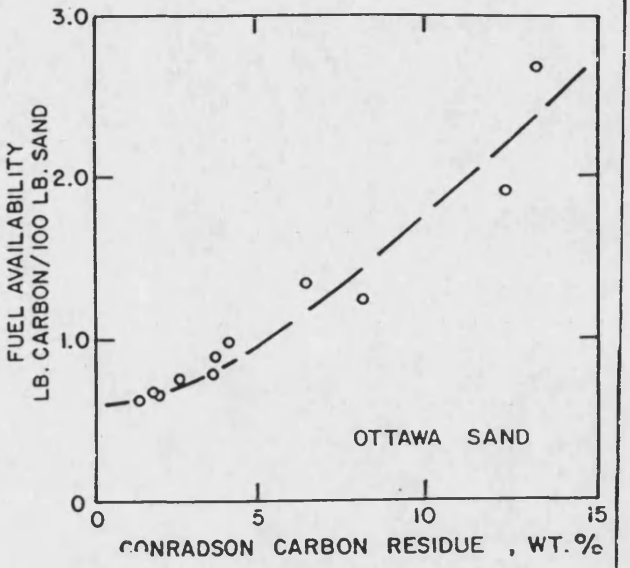


Fig (5-F) Effect of crude-oil Conradson carbon
on fuel availability.
(after Alexander et al, 1962)

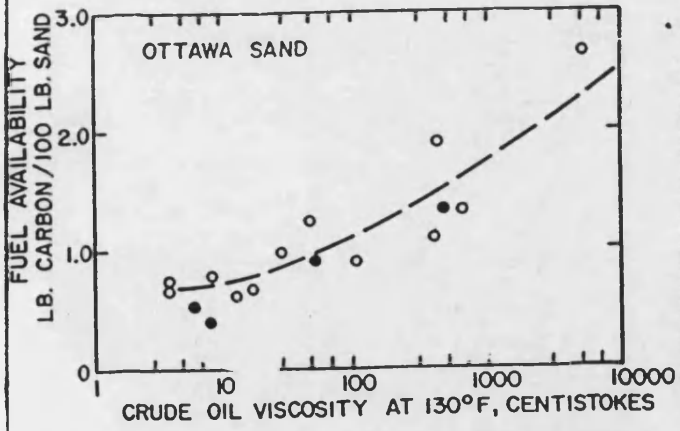


Fig (5-g) Effect of crude-oil viscosity on fuel availability.
(after Alexander et al, 1962)

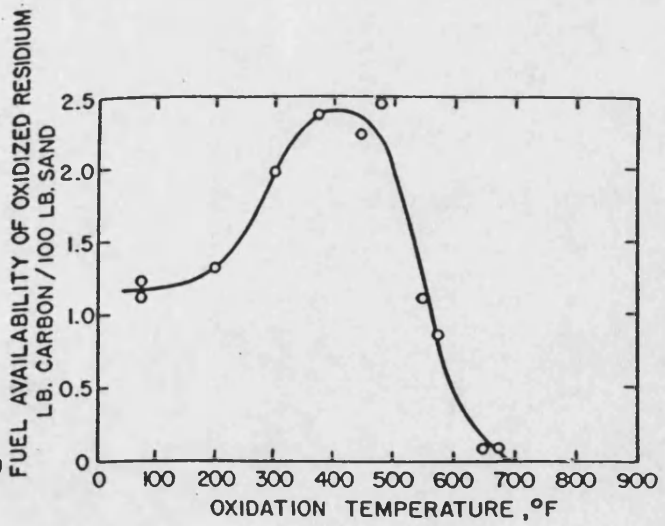


Fig (5-H) Effect of low-temperature oxidation on fuel
availability at 800° F.
(after Alexander et al, 1962)

These authors concluded that, fuel availability decreased as the C/H ratio, viscosity, Conradson carbon residue and oil saturation decreased and the API gravity increased.

The effect of clay and the sand matrix on fuel availability were studied and reported by **Bousaid et al, 1968** and **Vossoughi et al, 1981** .

Fuel deposition was found to increase with increase in the surface area of the rock matrix and the clay content. It was also reported, that pressure has some effect on fuel deposition, i.e. increasing slightly with increasing the pressure. Thus, increasing pressure suppresses vaporisation and distillation, so that the amount of residual oil is increased (**Abu-khamsin, 1987** and **Yannimaras and Tiffins 1995**). Low temperature oxidation, prior to the combustion, has a great effect on fuel deposition and hence combustion. LTO reactions increase the viscosity of the heavy crude oil, thus decrease the mobility of oil. As a result more residual oil is left which contributes to the fuel available for the combustion.

Dabbous and Fulton, 1974 reported that fuel deposition increased by 22% in the presence of LTO reactions. However, if the crude oil is light, LTO reactions can raise the reservoir temperature, so helping to displace the oil down stream, contributing to a decrease in the fuel available for combustion.

Mamora and Brigham 1995, investigated the effect of low temperature oxidation (LTO) on the fuel for heavy oil ISC. They reported that, high combustion temperatures were obtained when clay and fine sands were used. These small sand particles reduced the permeability of the sandpack and also provided a large reaction surface area. Consequently, the residual oil saturation and fuel concentration increased, resulting in high combustion temperatures.

Hughes et al 1996, used a continuous flow high pressure reactor to study the effect of formation type on the kinetics of heavy crude oil combustion. They concluded that, the type of formation significantly affects the nature of reactions of the in-situ combustion. When LTO occurs in unconsolidated formations, a heavier residual oil is produced, and visbreaking is more effective, leading to larger amount of coke and higher fuel deposition, with a smaller H/C ratio of the fuel burned.

Kisler and Shallcross 1996, studied the effect of metallic catalysts on light oil oxidation, they reported that some metallic catalysts such as Sodium, Copper and Iron enhanced the fuel combustion reactions. While Lithium, Magnesium and Cobalt reduced the amount of fuel available.

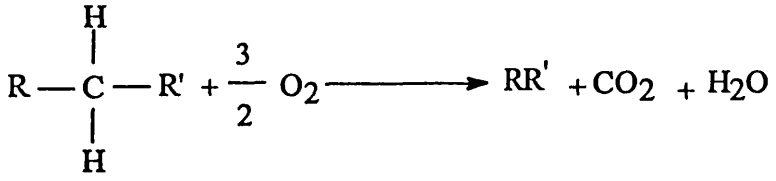
Castanier and Brigham 1997, reported that, metallic additives such as Copper, Nickel, Iron and aluminum caused changes in the both nature and amount of fuel formed during in situ combustion . These changes appear to depend on the type of oil used.

2.7 Kinetics of in-situ combustion

2.7.1 Oxidation reaction of crude oil:-

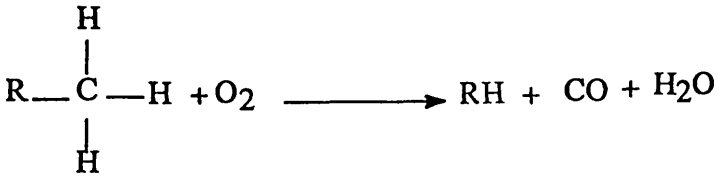
Oxidation of oil is achieved whenever it comes into contact with oxygen. Oxidation is affected by the composition of oil and also the temperature at which the oxidation takes place. In practice, hydrocarbons are converted into a wide variety of oxidation products when they react with oxygen e.g. alcohols, aldehydes, ketones, carbon oxides, carboxylic acids etc. All these reactions are very exothermic; the heat liberated is between 90 and 105 kcal/mole of oxygen consumed(**Burger and Sourieau 1980**). Some of the oxidation reactions can be written as follows :-

Complete combustion,



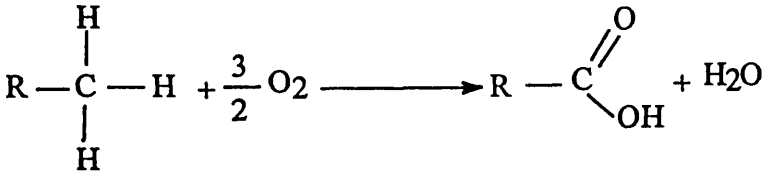
$$R-\underset{\underset{H}{|}}{\overset{\overset{H}{|}}{C}}-R' + \frac{3}{2}O_2 \longrightarrow RR' + CO_2 + H_2O \qquad (2.3)$$

Incomplete combustion,



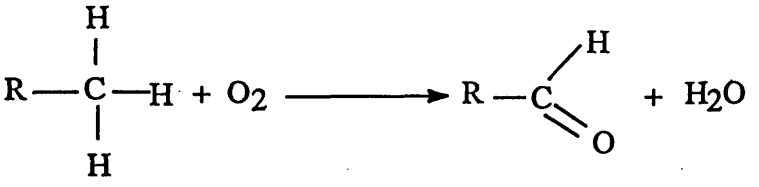
$$R-\underset{\underset{H}{|}}{\overset{\overset{H}{|}}{C}}-H + O_2 \longrightarrow RH + CO + H_2O \qquad (2.4)$$

Oxidation to carboxylic acid,



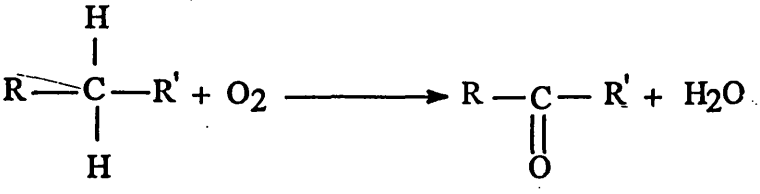
$$R-\underset{\underset{H}{|}}{\overset{\overset{H}{|}}{C}}-H + \frac{3}{2}O_2 \longrightarrow R-C(=O)-OH + H_2O \qquad (2.5)$$

Oxidation to aldehyde,



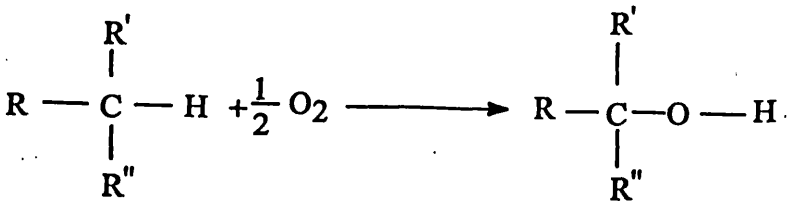
$$R-\underset{\underset{H}{|}}{\overset{\overset{H}{|}}{C}}-H + O_2 \longrightarrow R-C(H)=O + H_2O \qquad (2.6)$$

Oxidation to ketone,



$$R-\underset{\underset{H}{|}}{\overset{\overset{H}{|}}{C}}-R' + O_2 \longrightarrow R-\overset{\overset{O}{\|}}{C}-R' + H_2O \qquad (2.7)$$

Oxidation to alcohol,



$$R-\underset{\underset{R''}{|}}{\overset{\overset{R'}{|}}{C}}-H + \frac{1}{2}O_2 \longrightarrow R-\underset{\underset{R''}{|}}{\overset{\overset{R'}{|}}{C}}-O-H \qquad (2.8)$$

2.7.2 Oil Oxidation Kinetics

The reaction between the hydrocarbon fuel and oxygen in the forward combustion process is a heterogeneous flow reaction. For the combustion to proceed, it is necessary for the injected oxidant gas to pass through the burning zone. The burning zone moves as fuel is depleted by oxidation. Within the burning zone, a number of transport processes occur. As oxygen moves from the bulk gas stream to the fuel interface, it adsorbs onto surface and react with the fuel. Combustion products must then desorb and finally, transfer into the combustion gas stream. If any one of these steps is much slower than the remaining steps, the overall rate of the reaction will be controlled by that step.

The carbon reaction rate can be expressed by this formula:-

$$\frac{dc}{dt} = kc^a p_{O_2}^b \qquad (2-9)$$

where: c = carbon concentration on sand grains.

t = time a, b constants.

p_{O2} = oxygen partial pressure at the reaction interface.

The specific rate constant (k) may be related to temperature by the Arrhenius equation:

$$K = A\, e^{\frac{-E}{RT}}$$

where: A = Arrhenius constant or frequency factor.

E = activation energy.

R = gas law constant.

T = absolute temperature.

Bousaid and Ramey, 1968 who studied the burning rate of carbon as function of carbon concentration, combustion temperature and oxygen partial pressure, concluded that, the carbon burning rate of crude oil indicated a first order reaction with respect to both carbon concentration and oxygen partial pressure. **Dart et al,1949** who studied the combustion of carbonaceous residues on clay catalyst pellets, found the reaction to be second order with respect to carbon concentration and first order with respect to oxygen partial pressure.

Lewis et al, 1954 who studied the oxidation of charcoal coke and graphite in a fluidized bed, found a first order reaction dependency with respect to both carbon concentration and oxygen partial pressure. **Greaves et al,1987** who conducted a series of tests on medium heavy crude oil under dry and wet forward combustion using oxygen concentrations of 21 to 35% by volume, concluded that the reaction kinetics are dependent on carbon concentration and oxygen partial pressure. The addition of clay material increased the carbon concentration, but did not affect the reaction rate.

The ISC kinetics of Athabasca tar sands were investigated by **Hughes *et al* 1990,** they found that the extent of low temperature oxidation reactions and the rate parameters obtained for high temperature combustion reactions are influenced by the oxygen partial pressure in the feed gas. It was also observed that there was an increase in the heat released when oxygen concentration increased to 35%. The increased oxygen concentration also produced a decrease in the activation energy for the high temperature combustion reactions.

Rashidi and Bagci,1991 studied the effect of pressure and clay content on the combustion kinetics of heavy oil in a limestone medium . They concluded that ,the activation energy of all of the reactions involved in the combustion process

decreased with increasing clay content in the matrix, which is indicative of the catalytic effect of the clay. It was reported also that, the clay's surface area affects the Arrhenius constant.

2.7.3 Stoichiometry of In - Situ Combustion

The in-situ combustion process in fundamental terms is the propagation of a combustion zone through the porous rock of the reservoir. The produced heat and combustion gases causes the oil to be swept ahead of the front. The primary fuel to sustain combustion is derived from thermal cracking of oil.

The stoichiometry of the combustion process may be represented by the following equation (Burger, 1985)

$$CH_X + (1 - \frac{r}{2} + \frac{x}{4})O_2 \longrightarrow (1 - r)CO_2 + rCO + \frac{x}{2}H_2O \qquad (2 - 10)$$

Where $r = CO / (CO + CO_2)$

$x =$ the hydrogen / carbon ratio of the fuel (H/C)

Complete high temperature combustion will produce mainly CO_2 and water, hence the value of $CO/(CO+CO_2)$ will be almost zero. Values greater than zero are caused by varying degree of incomplete combustion. H/C , the atomic hydrogen to carbon ratio of fuel for ISC normally determines the type of fuel and the combustion mode ,which may be achieved. In the high temperature oxidation (HTO) mode, H/C tends to be below 2. However, the H/C value can vary due to the occurrence of low temperature oxidation below 300°C

The H/C ratio can be predicted using this equation:-

$$H / C = \frac{1.06 - 3.06yCO - 5.06(yCO2 - yO2)}{yCO2 + yCO} \qquad (2 - 11)$$

where y = mole fraction of components in produced gas

2.8 Chemical Reactions

The two main reaction occurring in the in-situ combustion process are the coke formation and coke combustion. Coke formation indicates the amount of fuel available for combustion, whereas the combustion process itself determines the velocity and the volume of the combustion front and thus the efficiency of the whole process. Generally, there are three types of chemical reaction involved in the process of in-situ combustion:-

Low temperature oxidation of crude oil (L T O).

Formation and deposition of coke by thermal cracking reaction

Combustion of coke (H T O).

2.8.1 Low Temperature Oxidation (L T O).

Partial oxidation or low temperature oxidation(LTO) occurs in zones where the temperature is lower than 300°C. These partial oxidation reactions produce primarily water and oxygenated hydrocarbons such as carboxylic acids, aldehydes, ketones and alcohols **Burger et al,1972**. The oxygenated products can have significantly higher viscosity, lower volatilities and lower gravity than virgin oil in the case of heavier oils. **Dabbous and Fulton,1974** reported that (LTO) can take place in dry forward combustion when oxygen is available downstream of the combustion front due to:

(a) incomplete oxygen consumption in the high temperature combustion zone. **(b)** a channelling. **(c)** a tilted combustion front surface causing gas override.

Oxidation of crude oil at temperature below 300°C has a significant effect on the behaviour of the crude oil/water system in porous media and on the fuel available for combustion. Light oil appears to be more susceptible to partial oxidation at low temperature because of its relatively high hydrogen content. Most of the reacted oxygen is consumed by hydrogen and hydrocarbon oxidation rather than by carbon oxidation. Low temperature oxidation reactions are in most cases, undesirable because of their adverse effect on the viscosity and distillation characteristics of the crude(especially for heavy oil). This is because of the fact that displacement of oil in the reservoir by in-situ combustion is ultimately controlled by the physical properties and distillation characteristics of the crude. LTO reactions can seriously affect the process performance particularly oil movement, fluid saturation and fuel availability.

Alexander et al,1962 , who studied the effect of LTO on 21.8°API crude oil found LTO reactions had a dominant effect on fuel deposition and composition. The formation of coke increased to a maximum at 218°C and then decreased sharply to zero at about 450°C. It was found also that LTO reaction increases the viscosity and the boiling range of oil. **Dabbous and Fulton,1974** found that the amount of fuel deposited in presence of LTO reactions increased by 22% and that the properties of the fuel, such as hydrogen content, colour and structure were quite different from those runs which were conducted in the absence of LTO reactions. **Fassihi et al 1990,** studied LTO reactions of four oils, ranging from 31.1 to 10.1°API and from 14 to 54,300 cp. They concluded that the LTO of these oils was a function of reaction time, oxygen partial pressure and temperature. LTO increased oil viscosity and density. For lighter oils, these increases were minor and had insignificant effects on process performance.

For the heavier oils, the viscosity of the oxidised oils increases exponentially with increasing extent of oxidation. **Hughes *et al* 1991** found that the particle size of the sand matrix has an important influence on the relative magnitude of the heat released in the LTO region. Decreasing particles size i.e. increasing the surface area of the sand increased the LTO exotherm and reaction period. **Mamora and Brigham, 1995,** reported LTO occurrence due to low fuel concentration, which resulted in a reaction temperature of only 350^{0}C, compared to 500^{0}C for HTO. Also when oxygen moved ahead of the reaction front, an oxygenated hydrocarbon fuel was found, and the produced oil viscosity and specific gravity increased.

2.8.2 Thermal cracking

Thermal cracking of crude oil is defined as the change in oil composition when it is heated in the absence of oxygen. In the cracking process the C-C carbon bonds are broken and shorter molecules are formed. The reaction may be represented as:-

$$\textit{Heavy Hydrocarbon} \xrightarrow[\textit{cracking}]{\textit{thermal}} \textit{Light Hydrocarbon} + \textit{Heavy Residue}$$

Abu Khamsin *et al* 1987, presented a comprehensive concept of the pyrolysis of crude oil in porous media. The three comprising stages were:

(**i**) distillation, in which the oil loses most of its light fractions and part of its medium gravity fractions. (**ii**) visbreaking, in which the oil undergoes mild cracking to slightly lighter products. (**iii**) coking at high temperature. The remaining oil in the porous media cracks to a semi-sold residue that is rich in carbon (which represents the fuel for high temperature combustion)

It is thought that the dominant mechanism for coke deposition(fuel) is thermal cracking, although some investigators believe that vaporisation and pyrolysis reactions both contribute to fuel deposition. **Belgrave,1990** considers that thermal cracking alone is not sufficient to account for all of the fuel produced in the ISC process, a considerable, or even major source occurs through LTO.

Thermal cracking is not only important because it produces a heavy fractions and coke-like material, but also because it can affect the vaporization and pyrolysis processes as a result of changes in oil properties such as viscosity and specific gravity.

2.8.3 High Temperature Oxidation (HTO)

High temperature oxidation reactions can be defined as the reactions which take place in the high temperature combustion zone above 315°C, with CO_2, CO, and H_2O as the principal reaction products. High temperature oxidation or fuel combustion is the main factor responsible for generating heat in the reservoir i.e. the principle mechanism for the in-situ combustion process (**Lerner *et al* 1985**).

The effectiveness of in situ combustion depends on the rate at which heat is generated by the combustion process and the efficiency of the heat utilisation, which in turn depends on reservoir fluid distribution and the thermal properties of the reservoir rock matrix and the surrounding rock. The rate of heat generated by the in-situ combustion process, depends mainly on the reaction rate, which depends on fuel concentration, oxygen partial pressure and air injected rate according to Eqn.(2-9). The type of fuel and its amount can be determined from the peak temperature and the extent of the HTO.

reactions. The combustion front advance is related to the quantity of fuel available for combustion. The HTO reactions are affected by LTO, which can affect the amount and type of fuel (**Fassihi et al 1990**).

2.9 Factors Affecting the In-Situ Combustion Process

2.9.1 Clay

Extensive research has been done on the effect of clay materials and surface area on the process of in-situ combustion. The main conclusion is that, the surface area combined by the addition of clay materials into the sandpack matrix has a significant effect on fuel deposition and combustion rate.

Vossouhi *et al* 1981 investigated the effect of clay in four dry in situ combustion experiments. Sandpack mixtures containing varying amounts of clay (kaolinite) were saturated with crude oil (medium to heavy) and water. One experiment was also performed with amorphous silica powder to compare with clay tests. More fuel was deposited as the clay content of the sand was increased, causing the combustion peak temperature to increase. The higher fuel deposition was due to the high surface area contributed by the clay. The effect of sand grain size was also investigated. Sand grains of low specific surface area did not sustain combustion, while those with high surface area produced a strong self sustained combustion front. Similar results were obtained by **Quarda and Shapour 1985** and **Bagci 1991.**

Greaves.*et.al* 1987 carried out in situ combustion study on North sea Forties and Maya crude oils, they concluded that increasing the clay content from 5 to 10% increased the air required by about 30% due to increased fuel availability.

Vossoughi *et al* 1983 and **Rashidi and Bagci 1991,** reported a significant reduction in the activation energy of the crude oil combustion resulting from the addition of clay. This can be referred to the fact that, clay minerals mostly consist of silica and alumina which are classified as solid acid catalysts. Their catalytic activities are related to their acid site density and strength. Activation energy decreases with increase in acidity.

2.9.2 Pressure

Wilson *et al* 1963 , conducted combustion tube tests at pressure of 14.7 to 1000psig, for five types of crude oil of low and intermediate gravity, using forward and reverse combustion. For forward combustion, increasing the pressure increased the peak temperature but decreased the velocity of the combustion front. For reverse combustion; increasing the pressure resulted in a lower peak temperature but an increased rate of advance of the combustion front. Carbon dioxide formation was a linear function of temperature, depending on pressure and air flux.

Prasad and Slater 1986, who conducted some of the highest pressure combustion tests, up to 3000psig summarised several phenomenon which may affect the high pressure in-situ combustion process:

1 Carbon dioxide, produced during high pressure in situ combustion process is more soluble, reducing the oil viscosity and improving oil displacement.

2 At high enough temperatures and pressures i.e. the critical condition, the water polarity is reduced substantially, approaching that of oil. The two liquids tend to become soluble, greatly improving the displacement efficiency.

3.- The higher partial pressure of oxygen at combustion front leads to more effective combustion and high oxidation rates.

Hughes *et al* 1991 used the high pressure differential scanning Calorimetry (DSC) to evaluate oil sands for the in situ combustion process. They reported, increased pressure reduced the oil volatility, increasing the oil available for combustion, creating more stable combustion under a large range of conditions.

Tiffin and Yannimaras1995 have studied the effect of pressure on light oil combustion. Experiments with two different light oil reservoirs, were conducted at pressures ranging from 6.9 to 37.2 Mpa in an automated high pressure combustion tube. The volumetric oil recovery was more than 90% for all tests. They concluded that the effect of pressure was:- **(a)** high injection rates of air are needed to operate under high pressure. Attempts to run the experiments at low rates resulted in low temperature, oxygen breakthrough, and inability to propagate the combustion front, **(b)** calculated air/fuel ratios were relatively constant with pressure, whereas fuel deposition and air requirement increased slightly with pressure, **(c)** excellent displacement efficiency was obtained.

2.9.3 Oxygen Enrichment

The use of oxygen, or enriched air, for in-situ combustion may offer several potential technical and economical advantages over similar air combustion.

Hansel.*et.al* 1984 built and operated a high pressure combustion tube system for oxygen enrichment studies. Their objective was to evaluate the combustion characteristics of light oils with low value of initial oil in place using different levels of oxygen enrichment. (21% to 95%O_2) at constant gas influx.

They found that combustion with air and 30% oxygen was unsatisfactory, whereas combustion with 40% to 95% oxygen was more satisfactory.

The CO_2 content increased with oxygen enrichment, and the Combustion front velocity increased with the time required to produce initial oil decreased substantially. The total injected gas required per barrel of oil produced decreased with oxygen enrichment. Most importantly, oxygen enrichment combustion can sustain ISC under conditions, where it may not be possible using air. The H/C ratio, maximum combustion temperature, oxygen utilisation efficiency and CO_2/CO ratio did not change when oxygen enrichment was used. **Shahani and Hansel 1987**, investigated five light, medium and heavy crude oils, at 750 and 2000 psi and with oxygen concentrations between 21% to 95%. Their main conclusion was that, oxygen enrichment was useful for sustaining combustion under conditions where air was unsatisfactory. **Petit 1990** carried out combustion tests on two heavy oils having low API gravities, using air and oxygen enriched. He concluded that the $CO/CO+CO_2$ ratio of the combustion gases decreased steadily from 0.12 to 0.05 when oxygen concentration increased from 21% to 100%. Petit was not able to conclusively demonstrate any positive benefit of using oxygen enrichment for these heavy oils.

Shahani and Gunardson 1994 studied the application of both pure oxygen and enriched air for light oil recovery and concluded that, there are positive benefits to be gained by using oxygen enrichment, namely, faster oil production, lower injection gas required and increased carbon dioxide levels.

2.9.4 Water Air Ratio (WAR)

The main purposes of injecting water with air in forward in-situ combustion is to: **(i)** recover the stored heat behind the combustion zone and transport it downstream, and **(ii)** to lengthen the steam zone . The large volume of steam sweeps the pore volume ahead of the combustion front, enhancing the displacement efficiency. In the case of normal or incomplete wet combustion, the water flowing through the combustion zone is in the gas phase. This is because the peak temperature is higher than the vaporisation temperature of the water. The process is called normal wet combustion when the deposited coke is completely burned, but when the cooling effect of the injected water is too high, the residence time of the coke in the high temperature zone may not sufficient for its complete combustion. Super wet or quenched combustion occurs when the WAR water is sufficiently high that, the heat available behind the combustion front is too low to vaporise all of the water reaching the combustion zone . In this case the combustion zone moves at the speed of the injected water. The major benefit of so-called combined forward combustion and water (COFCAW) is the threefold or more reduction in the amount of air required to recover a barrel of oil.

Burger and Sahuguet 1973 found that in wet combustion, the combustion front velocity was higher than for dry combustion, increasing as the WAR increased. When water is injected along with air, the fuel deposition decreases as result of the more efficient sweep by the larger steam zone .

Greaves *et al* 1987 carried out combustion tube tests to study dry and wet forward in-situ combustion using three different crude oils ranging from 36.6 to 22.1API.

They concluded that a considerable reduction in air requirement occurred with wet combustion. Changing the mode of combustion from dry to wet greatly reduced the amount of fuel burned and at a WAR=3.75 the fuel consumption was only 31% of that required for dry combustion.

Moore *et al* 1988 investigated the effect of water injection with air on oil recovery for Athabasca bitumen, they concluded that, the fuel consumption and air requirement decreased with increasing (WAR). The normal wet tests also provided higher recoveries than the corresponding dry runs.

Moore *et al* 1997 have reviewed the in situ combustion in Canadian heavy oil reservoirs, and the problems and perspectives. They reported that, based on laboratory observations the most stable burning performance is seen with the normal wet combustion mode. The peak temperatures are similar to those for dry combustion, but oxygen and air requirements are generally less. (approximately equal to the lowest value observed during dry combustion)

2.10 In-Situ combustion in light crude oil reservoirs

The in-situ combustion technique is mainly suitable for heavy oils due to its high viscosity and fuel potential. However, in-situ combustion has been shown to be technically feasible also in light oil reservoirs.

An early investigation by **Alexander *et al* 1962** on the factors affecting fuel availability, concluded that fuel availability decreased as the API gravity and H /C ratio increased. Miscible gas displacement plays a relatively more important role in reservoirs containing light oil since more volatile components are vaporised to a relatively large extent at the heat front. This results in upgraded oil which can be displaced faster by the flowing steam and water bank. **Parrish *et al* 1969**, carried out seven pilot tests to evaluate the COFCAW process using six light crude oils with API gravities between 30 and 40.6 API, and found that at reservoir temperatures of 85°C and above, the oxygen was completely consumed.

Hardy *et al* 1972, carried out a pilot test in the May-Libby reservoir of the Delhi field of Louisiana. They concluded that in situ combustion can be successfully employed to recover crude oils having a gravity as high as 40 API gravity, but added that the mineralogy of the host matrix can have a great influence on the process variable of in-situ combustion.

Garon *et al* 1974 conducted combustion tube tests on twelve different crudes which included 32.8, 37.3, 40.2 API gravity. They found that all crudes sustained dry forward combustion under atmospheric and 6.9Mpa pressure.

The process of in-situ combustion has been used to enhance oil recovery from light oil reservoirs as deep as 11,500ft since 1970. Gulf successfully injected air at 3000psig to enhance oil recovery from the Cotton valley sands, located at an average depth of 11,500ft in the West Heidelberg field in Mississippi(**Prasad and Slater 1986**) .

The fuel availability for in-situ combustion with light oil seems to be the main potential difficulty of using this technique. The two principal factors that control the amount of fuel deposition are; (i) fuel composition reactions, and (ii) the process of displacement which determines the amount of undisplaced oil.

Shahani *et al* 1987 conducted a study on five light, medium and heavy crude oils in a combustion tube at pressure ranging from 750 to 2000 psig and with oxygen enrichment between 21% and 95%.; it was concluded that, for medium and light oils at concentrations of 40% O2 or more the combustion was satisfactory. The main advantage of oxygen enrichment was that, combustion could be sustained under conditions where air was unsatisfactory.

(Tzanco *et al* 1990) performed 15 laboratory in situ combustion tube tests using a 28^{0}API oil from the Countess B pool located in Southeastern Alberta, using air. The tests included dry , normal wet and super wet combustion . The primary results from this study were that the Countess B oil did not appear to be burning as coke like fuel but, rather it appear to be burning as an oxidised asphaltenes fraction. The low rate of coke deposition was the main problem reported in sustaining high temperature combustion .

Generally, when air is injected into a light reservoir, exothermic chemical reactions occur between the oxygen and the reservoir oil. These reactions, in case of light oil are mainly oxidation reactions resulting in heat generation and production of oxides of carbon(CO, CO_2). The chemical reactions are dependent on the oil characteristics, rock / fluid system, temperature and pressure. The heat generated results in temperature increase, leading to vaporisation of the lighter components.

The driving gas, therefore is not the injected air, but the in-situ generated flue gas (CO, CO_2, N2)and the vaporised light hydrocarbon components**(Sakthikumar *et al* 1995)**

Greaves *et al* 1995 carried out 3D in-situ combustion tests using light Forties crude oil. The experiments were done in a rectangular combustion cell using a vertical injection and horizontal producer well (VIHP). The results can be summarized as follows:

when a horizontal producer well in line drive was used, a high combustion zone temperature was sustained at reasonably high combustion front velocity.

The CO2 levels in the produced gases were generally low during the air tests, at around 10% or less, but were much higher when oxygen was used, averaging 14%. Under dry combustion conditions, the high water saturation present initially in the sand pack(Swi 35-45%) led to the development of a substantial steam - gas drive with volumetric sweep approaching 100%.

Tiffin and Yannimaras 1995, have made some of the most significant high pressure combustion tube tests on the performance of light oils at pressure ranging from 6.9 to 37.2 Mpa . These tests used both reservoir and artificial sands with two different types of crude oils of 28 and 34 API gravity. The main conclusion is that in situ combustion can be used for light oil recovery at high pressure. Flue gas generation(15% CO_2 and 81% Nitrogen) and oil displacement characteristics were good at all of the pressures investigated. Reservoirs sand tends to improve the light oil air injection process compared to outcrop sandstone.

Kisler and Shallcross 1997 used an effluent gas analysis (EGA) technique to study the reaction kinetics of light crude oil. They reported that, the oxidation behaviour of light oils is substantially different to that of heavy oils. With light oil, there are three peaks in the oxygen consumption versus temperature curves, whereas the data for heavy oils feature only two peaks. Oxidation reactions for light oil may be classified into three categories, as low, medium and high temperature oxidation (LTO, MTO, HTO). It was also observed that LTO for light oil involves the production of some carbon oxides which does not occur with heavy oils

CHAPTER THREE

COMBUSTION TUBE FACILITY

3 Main Components of the Combustion Tube Facility

The majority of combustion tube systems used for research are a thin-walled tubes filled with reservoir, or artificial material. The combustion tube is inserted into a thick outer vessel capable of withstanding high operational pressures. The annular space between the tube and container pressure vessel is filled with a porous insulation in order to reduce heat losses. The annular space is pressurised to support the inner tube. In order to simulate an adiabatic condition as exists within the reservoir, the tube is provided with electric heaters along the length of the thin walled vessel. These are used to minimise and control heat loss along the tube.

A flowsheet of the combustion facility is shown in Fig 3.1. The equipment can be divided into four main sections according to their individual function. These are:

(1) Pressure shell and combustion tube. (2) Gas feed supply system.(3) Fluid separation equipment. (4) Collection and analysis of combustion products. (5) Computer software and control.

3.1 Pressure Shell and Combustion tube

The pressure shell was constructed from carbon manganese steel and designed to withstand pressure up to 330 bar. This will allow experiments to be operated under pressure up to 240 bar and combustion zone temperatures up to 1000C. The shell and tube are shown in Fig. (3 - 2)

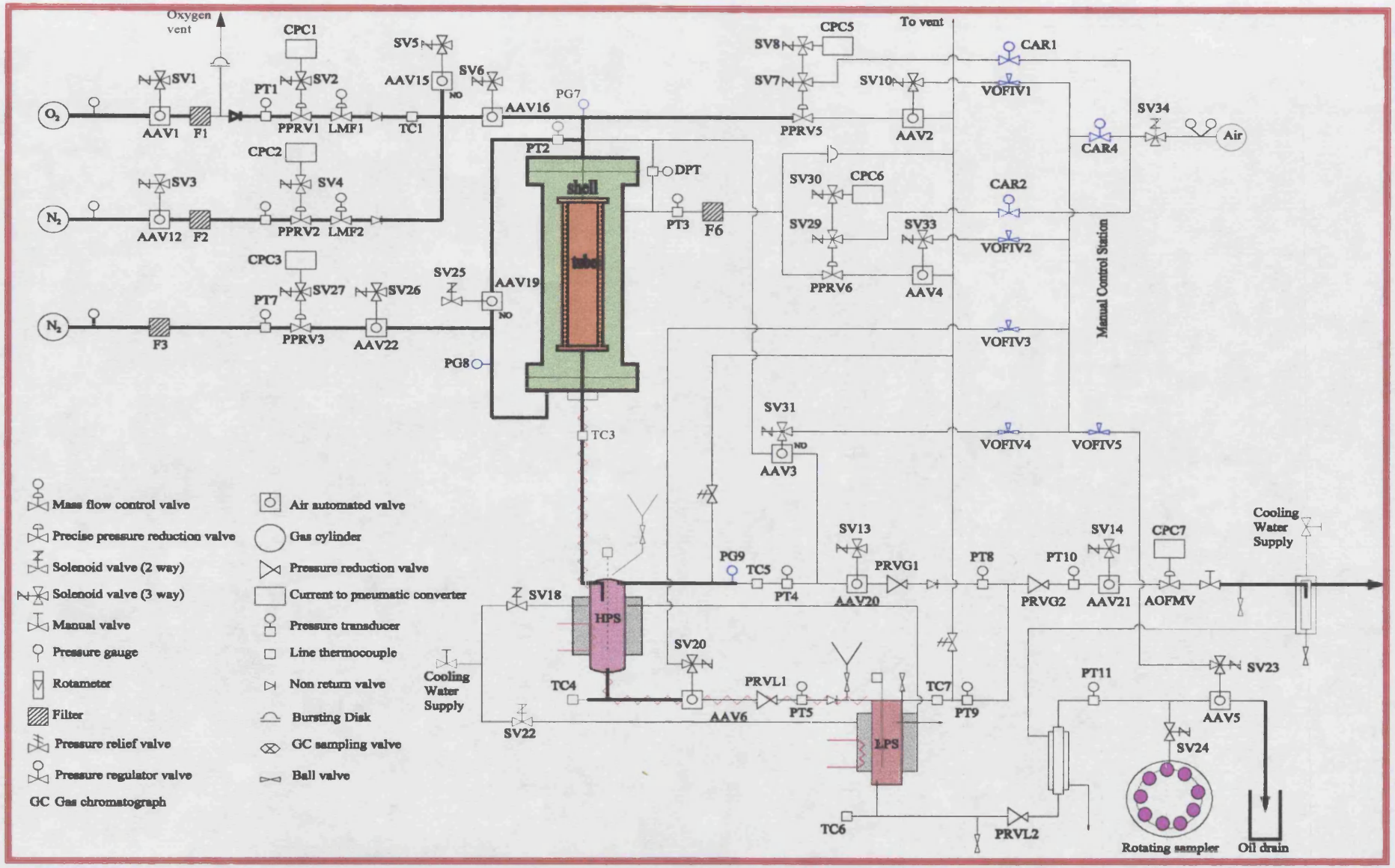


Fig 3.1 Flowsheet of the high pressure combustion tube system

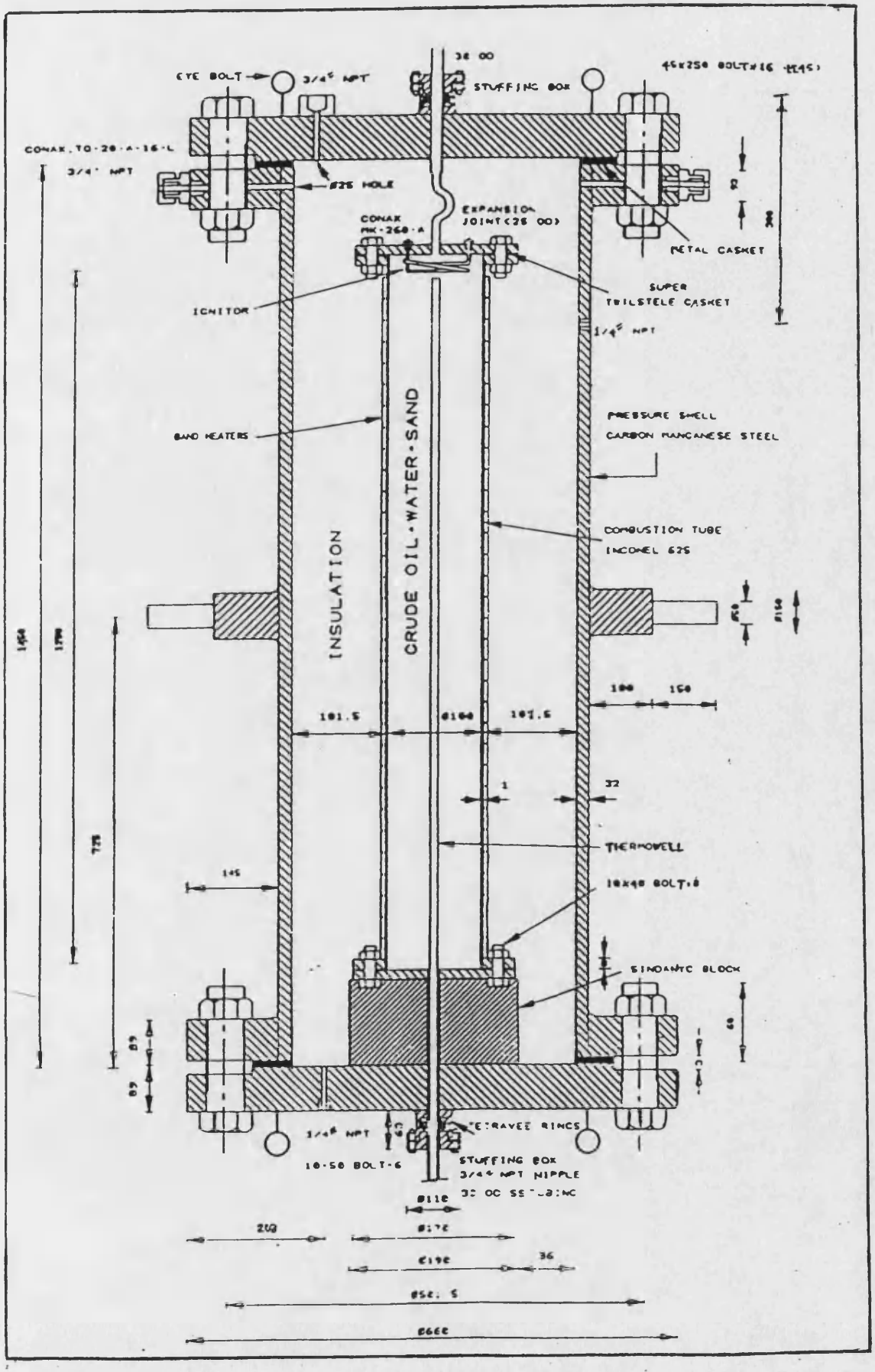


Fig 3.2 Schematic draw of the Combustion Tube and Pressure Shell, after Rayes 1992.

The pressure shell is 1450 mm in length and 300 mm inside diameter. There are two 1/4" openings (stainless steel Swagelok connections) on the body of the shell, one at the bottom end flange which is used to pressurise the annulus with nitrogen and the other one is 300mm from the top which is used for depressurising the annulus.

The combustion tube is a cylindrical tube of 2mm wall thickness, 100mm inside diameter and 1250mm long. It is made from INCONEL 625, which has outstanding corrosion resistance and a lower thermal conductivity. A second tube fabricated from 304 stainless steel, having the same wall thickness, was used for this work. The tube is surrounded with 32 circular band heaters in order to maintain the combustion process under essentially adiabatic conditions. Each band heater is 38mm wide and 2mm thickness with a nominal power output of 700 watt. In practice, the heaters are limited to approximately 50% power rating. An axial thermocouple probe is utilised to measure the average sand temperature at 32 locations along the central axis throughout the length of the tube, corresponding with 32 wall temperature thermocouples. The ignitor is fixed on the top flange of the tube. It is a tubular wire heater with a diameter of 80mm and a heated length of 50mm.

The annular space between the tube and the pressure shell is filled with Vermiculite insulation to reduce heat loss and protect the pressure shell from excessive temperature rise.

3.2 Gas feed supply system

The gas supply system consists of a group of oxygen and nitrogen cylinders supplies, connected to the combustion tube through flow control equipment and pressure sensors. There are three sources of gas as shown in Fig. (3 .3).

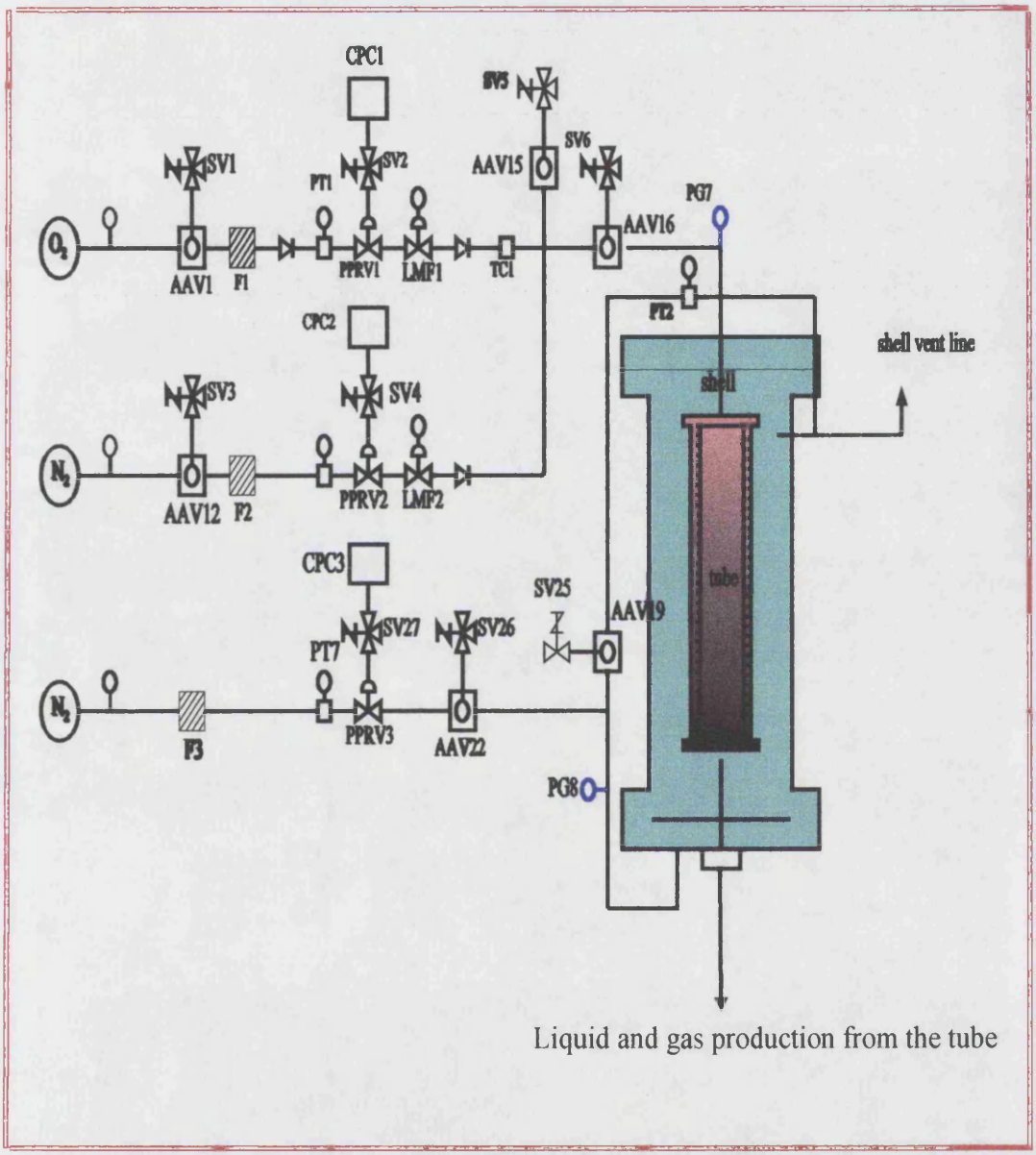


Figure 3.3 Gas supply lines to the combustion tube and pressure shell

Oxygen supply line

Oxygen of 99.5% purity is supplied from a cylinder at 230 bar. Oxygen is directed into the combustion tube under flow control. The injection pressure is measured by transducer PT1. An air activated solenoid valve AAV1 opens the line to the supply cylinder and a precision pressure regulator PPRV1 is used to regulate the flow via mass flow meter LMF1, which maintains the air to the combustion tube via ratio control with LMF2. Oxygen is mixed with nitrogen supply at air activated valve AAV16, then both gases enter the combustion tube as one air supply.

Nitrogen supply

This Nitrogen line is connected to a nitrogen cylinder at 230 bar. Nitrogen injection pressure is measured by the pressure transducer PT6. The air activated valve AAV2 opens the line to the gas cylinder and a precision pressure regulator PPRV2 and mass flow meter LMF2 regulate the flow.. Nitrogen is mixed with oxygen at AAV16 then injected into the combustion tube.

Pressurisation of pressure Shell and Combustion tube

Nitrogen via this line is used to pressurise the tube and the shell to the required operation pressure. It is used subsequently to maintain the differential pressure between tube and shell.

3.3 Liquid and Gas Separation

Fluid separation is the second most important part of the combustion tube facility. Its main purpose is to carry out separation of the multiphase fluid produced under high pressure and temperature. This requires special safety and operation procedures to be taken in consideration. The separation process of the combustion products happens takes place in two stages, comprises high and low pressure separators as shown in Figure 3.4

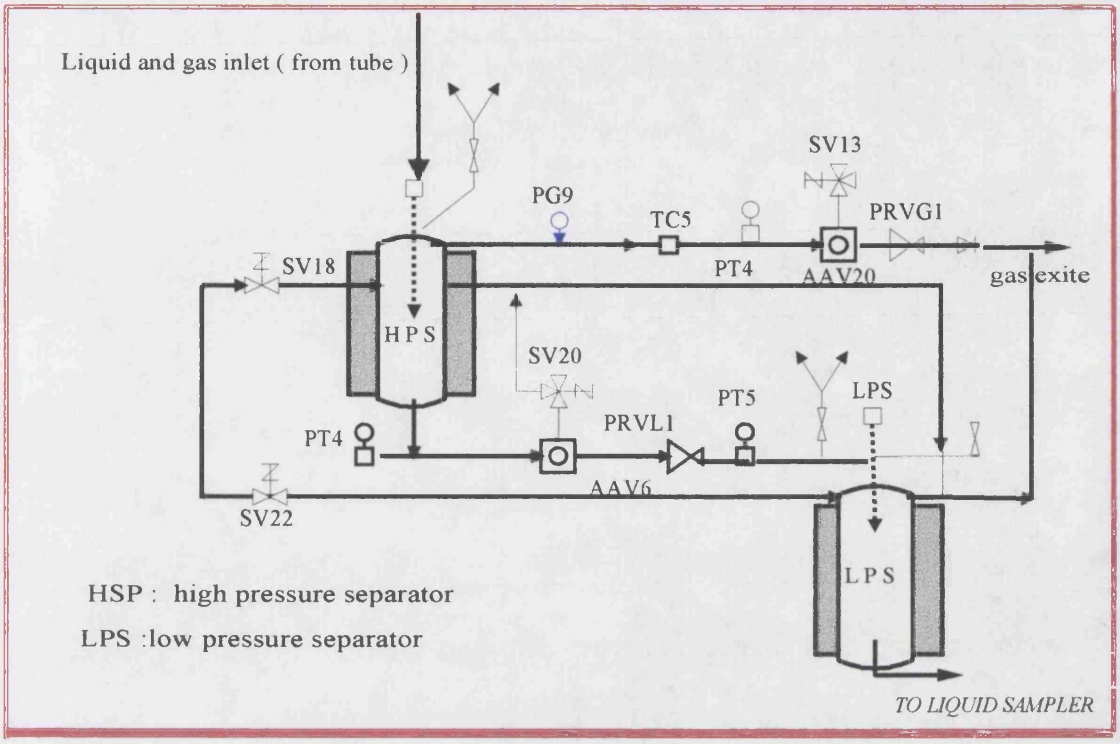


Fig. 3.4 Liquid and gas separation.stage

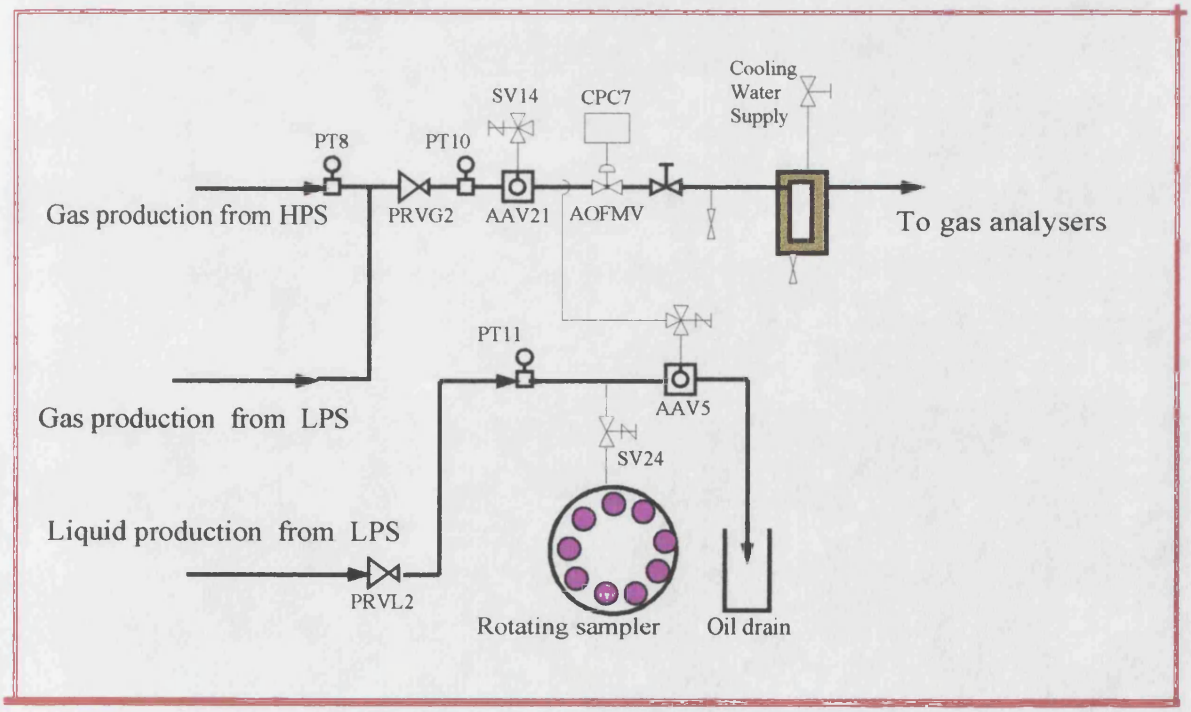


Fig. 3.5 Liquid and gas collecting stage.

High Pressure Separator _

Produced fluid from the combustion tube is passed first through the HPS. This vessel is made from 316 stainless steel and designed to operate at pressures up to 250 bar. The separator is provided with a specially designed float type level detector probe. As the liquid level rises inside the vessel, the magnet on the top of the detector probe closes a small electric circuit, via a positioned contact. This is indicated by a light display on the control panel. The vessel is provided with six individual circuits, arranged in a precise vertical sequence. This can indicate 12 liquid level positions, according to the particular float position.

The separator is provided with a rupture disc (RD3) to vent the gas in case the pressure inside it exceeds the predetermined operation pressure. A fine control valve (PLATON) is installed on the exit gas line to control the back pressure on the combustion tube. The liquid flow from the HPS is controlled by an air activated valve AAV18 according to the high level signal. AAV18 is closed when the liquid drops to the second liquid level position. This keeps 100 ml of liquid in the HPS at all times, to avoid any access of gas into the liquid line.

The separator is surrounded with a water jacket, and water is circulated to maintain a constant temperature of 60 to 80C in order to assist the separation process. A schematic drawing of the high pressure separator can be seen in Fig. 3.6.

Low Pressure Separator

The liquid product from the high pressure separator is throttled through a liquid spring loaded pressure reducing regulator (PRVL1), then liquid (oil and gas) enters the low pressure separator at pressure of 30 bar to 7bar .

The low pressure separator (LPS) is physically similar to the high pressure separator. It is also made from 316 stainless steel, and is designed to operate at a maximum pressure of 50 bar. Like the HPS, the separator is provided with the same type of float level detector. When the separator is full, liquid is discharged through the air activated valve AAV4 to the rotating sampler. The gas produced from the low pressure separator is mixed with gas coming from HPS after PRVG1.

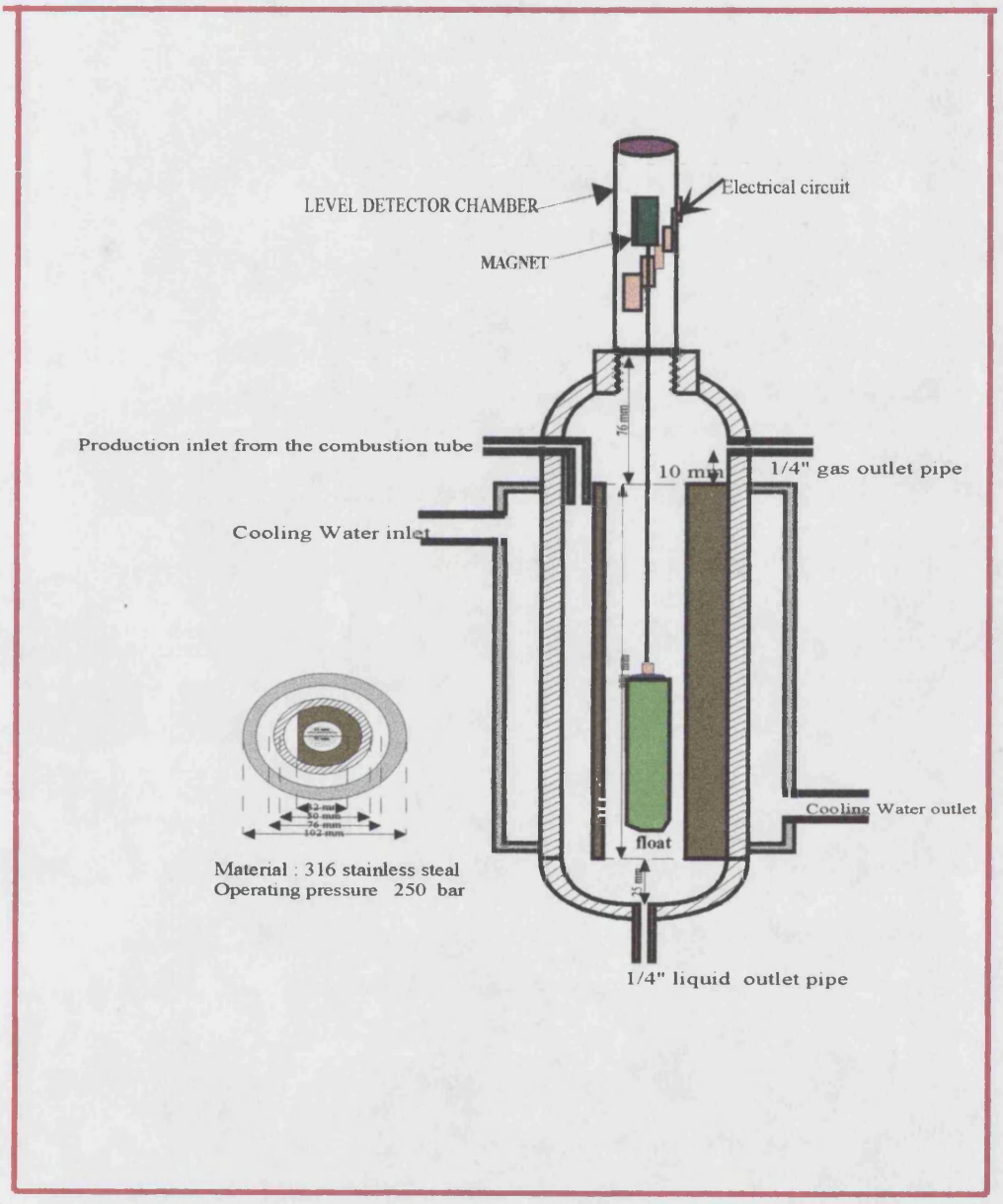


Fig. 3.6 High Pressure Separator (HPS)

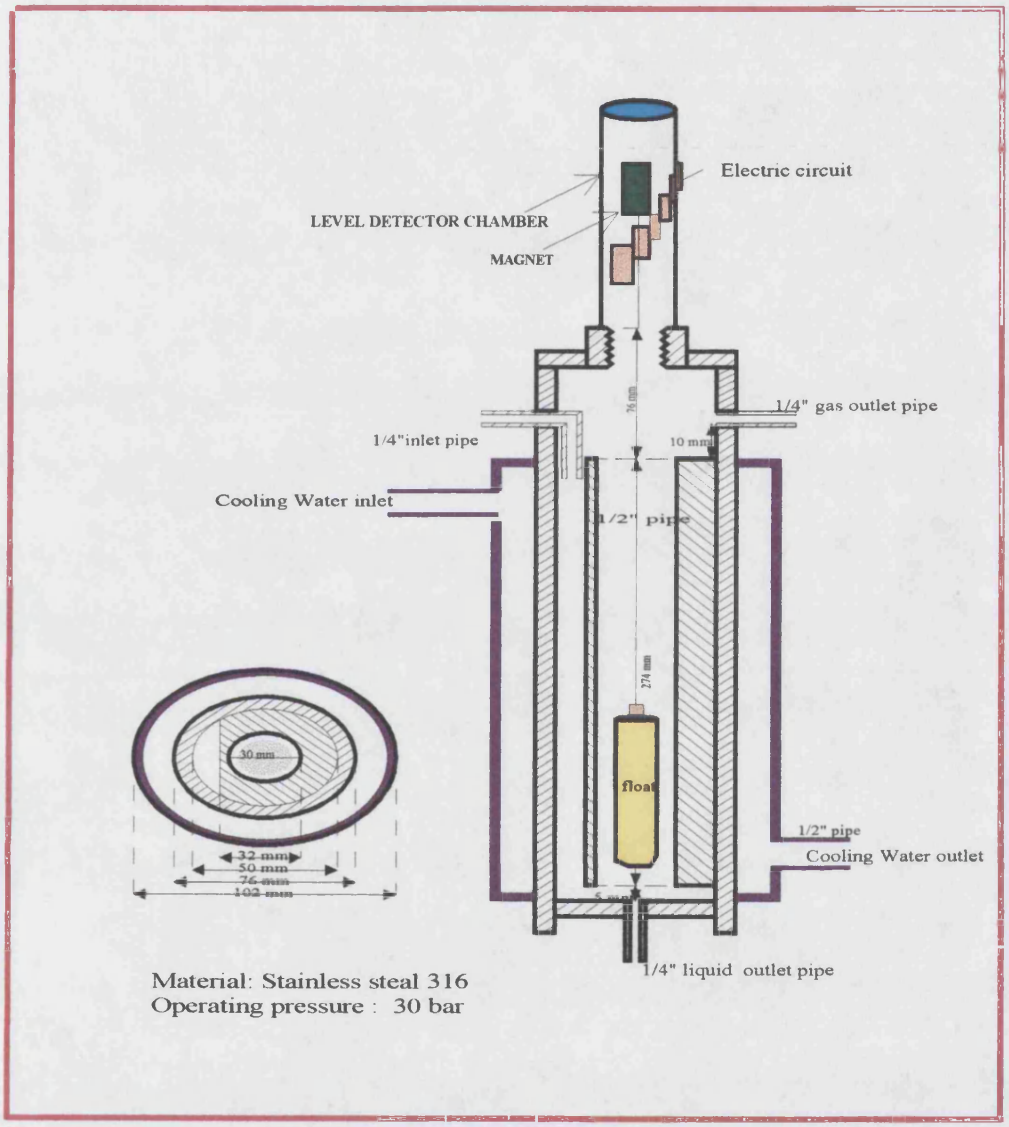


Fig. 3.7 Low Pressure Separator (LPS)

The mixed gas flow at 30 to 7bar is reduced by PRVG2 down to only 7psi, before being sent to the gas analysers, gas chromatograph (G C) and wet test meter (WTM). A diagram of the LPS is given in Fig. 3.7

3.4. Collection and Analysis of Combustion Products

A schematic drawing of the products collecting and analysis stage, can be seen in figure 3.5. When the LPS is full, at the 'high level' position, liquids are discharged through the liquid exit line. This is equipped with a thermocouple (TC6), which measures the temperature of the products. A pressure reducing regulator (PRVL2) is used to throttle the liquid down to atmospheric pressure. Pressure transducer (PT11) monitors the pressure down stream PRVL2. An on-off air activated valve AAV4 is used to finally discharge the liquid to collecting jars mounted on the liquid sampler. This is a 910mm diameter disc, loaded with 60 sample jars positions around the disc. The disc rotates automatically to the next collecting position following each discharge. Gases produced from the high and low pressure separators are mixed in a single line, and throttled by PRVG2 to 6 PSIG. The gas is then sent to the gas analysers which measure the percentage of O2, CO2, CO. A part of gas is passed through the gas chromatograph to measure the percentage of hydrocarbon gases, such as methane, propane, etc. Finally all of combustion gases are metered by a wet test meter to obtain the volumetric flow for precise measurement of produced combustion gases.

3.5 Computer System

One the most important aspects of the high pressure in-situ combustion tube facility, is the automation and control. In order to achieve this, 'Labview' graphical software was used and a computer program has been developed principally by Young and other members of IOR Research Group. **Young 1997.**

The multitasking data acquisition and control software uses a graphical language which makes it possible to animate the execution and see how data passes through the program at any time during the experiment. The computer system for data acquisition and combustion tube facility is shown in Fig. 3.8.

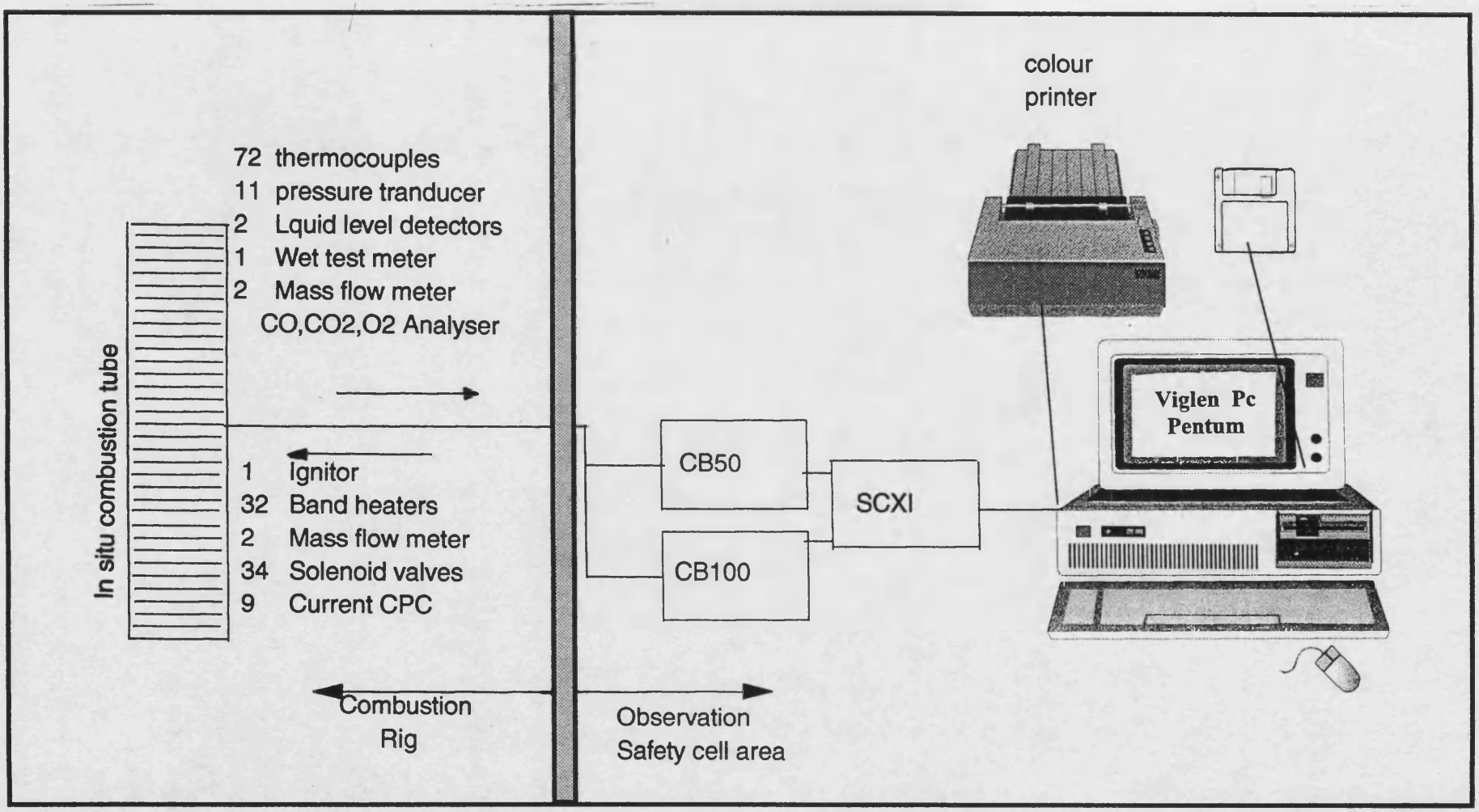


Fig. 3.8 Computer system for Data Acquisition and Combustion Tube

In the 'Labview' graphical programming language, any program or subroutine is made up of two parts, a front panel and the program diagram. The front panel shows the input, output data and indicators, while the diagram simply links the input to the outputs using the graphical language G which is icon based. Once a program is written an icon may be designed for it. The terminal can be then set up, so that program may be used as a subroutine (sub-vi) in an other program. Fig.3.8 shows the overall computer system layout used for data acquisition and control of in-situ combustion tube. If there is any failure during operation, it is easy to terminate or hold the run by the computer. It is also possible to carry out any development to the software tasks while the program is running. The experimental data is stored automatically by 'Lab View' on the hard disk.

In the event of an equipment or computer failure, the in-situ combustion rig is equipped with a manual control station in the observation safety area.

3.6 Manual Control Panel

The high pressure in-situ combustion system is dependent ultimately on the manual control panel in the event of equipment or computer failure. This panel must be checked and every item must be in perfect working order before operating the combustion tube system.

The control panel which is based in the observation area is utilised mainly to depressurise the combustion tube, pressure shell and the two separators when the experiment is emergency terminated .

The emergency manual control is used if one of following problems occurs:-

1. Failure of the main power supply.
2. Computer program failure.
3. Blockage of the combustion tube, production lines or the shell venting line.

The control station, which is shown in Fig 3.9 is consists of three pressure regulators, fed by air supply from 130 bar gas cylinder or directly by compressed air.

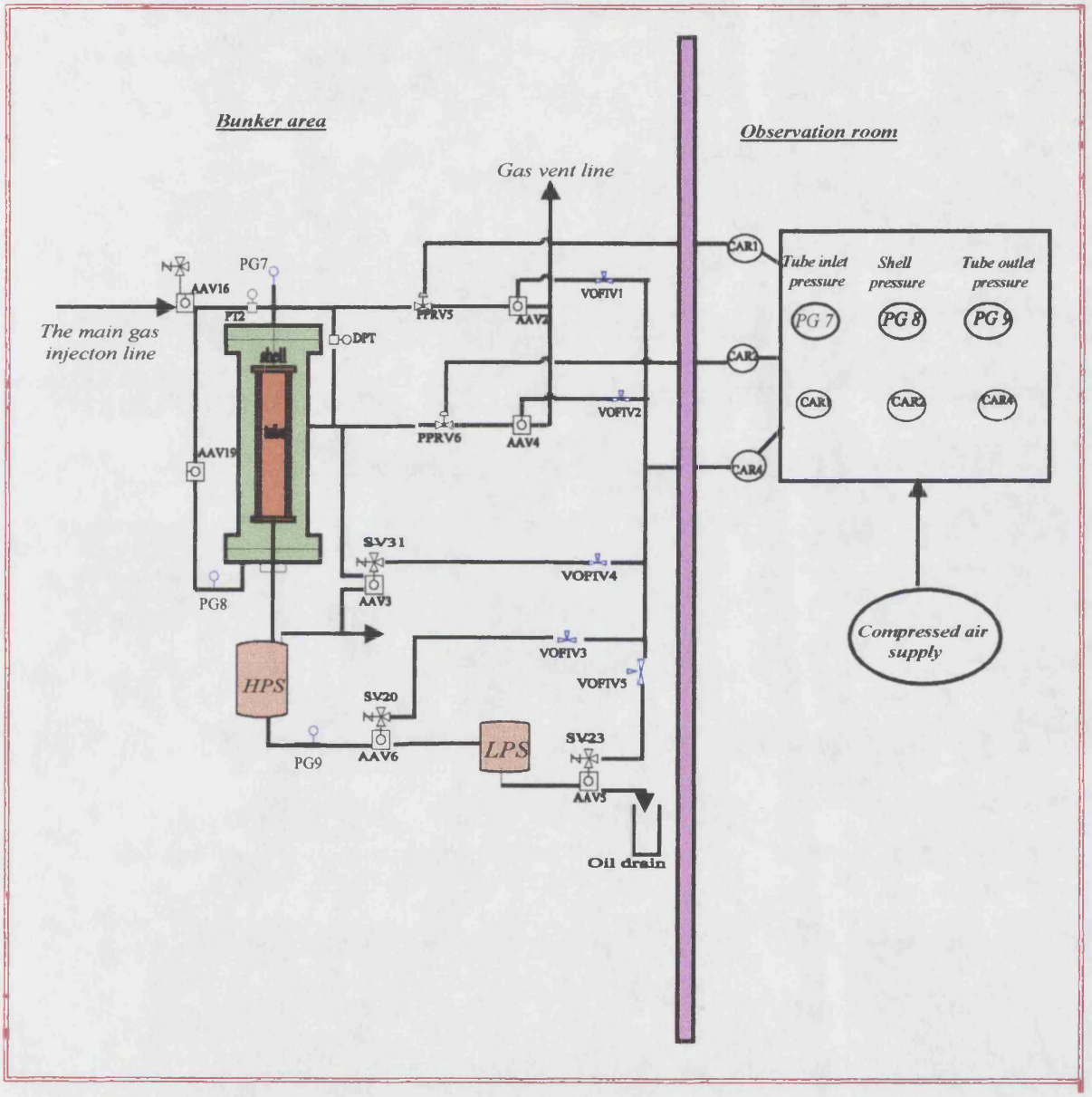


Fig. 3.9 Manual Control Station

Pressure regulator CAR1 supplies air to operate PPRV5, which vents the combustion tube via the main inlet gas line. Regulator CAR2 is used to operate PPRV6 to vent (depressurise) the pressure shell. The air supply regulator CAR4 is
used to open the emergency discharge system via the air operated valves (AAVs).
These valves are:

AAV2 - vents gas from the main inlet gas line at the top of tube.

AAV3 - opens the pressure shell to the tube, allowing a massive nitrogen flow from shell to extinguish a fire or to cool the system rapidly if required .

AAV4 - vents the shell and reduce the shell pressure when this cannot be performed from the computer program.

AAV5 - discharges liquid (oil + water) into the drain vessel in the event of an emergency termination of the experiment. The manual control station can also be seen as part of the main flowsheet of the system in Fig. (3 -1)

3.7 System Control Requirements

3.7.1 Pressure control

The system is designed to work at high pressure, and therefore require special pressure control equipment for this purpose. The inlet gas flow lines are controlled by three high pressure air activated precision pressure regulators (PPRV1, PPRV2, PPRV3). These regulators are remotely actuated with an air signal range from 2 to 80 psig. The air signal is supplied by electric current to pneumatic converters (CPCs).

The system operating pressure is controlled via the pressure regulator PPRV6 on the shell vent line and the main back pressure gas control valve (PLATON, Type M) on the main exit gas line.

Due to the sensitivity of the thin wall combustion tube to the differential pressure, the computer program is set to control the pressure differential in the range of less than 2 bar. In the case of an emergency, the combustion tube and injection gas line can be vented via PPRV5 on the main inlet line on the top of tube, while the shell can be vented via PPRV6, equalising the pressure on the shell and tube.

3.7.2 Flow rate control of the injected gases

It is essential to control the precise metering of the combustion flow rate of oxygen and nitrogen for the in situ combustion process. Inlet gas to the tube is determined by the mass flow controllers, LMF1 and LMF2. These controllers have an accuracy of 0.5% and are able to work at pressure ranges of 50 to 150 bar, or higher (up to 300bar) if recalibrated. LMF1 is installed on the oxygen injection line, it delivers a stable gas flow with full range of 0 to 3 litre/ minute. LMF2 is used to control the nitrogen flow rate into the combustion tube at flow range of 0 - 10 litre/ minute.

Both mass flowmeters are overridden during the stage of pressurisation, and as soon as that stage is completed, the flowmeters should start immediately delivering gas into the system at the pre set rates.

3.7.3 Adiabatic Temperature Control of the Combustion Tube

It is essential to achieve good adiabatic temperature control of the ISC tube system. In the absence of this control , there will be a large heat loss which can affect the combustion temperature and the propagation process.

Temperature control of the combustion tube is achieved using 32 band heaters stacked along the whole tube length. These heaters are used first to raise the sand matrix temperature to the reservoir temperature then, as soon as ignition is initiated and the combustion starts to propagate, the band heaters must be placed on the adiabatic mode to control any heat loss of the combustion temperature. The band heaters are 700 W mineral insulated devices, operated from 240 V mains supply and controlled by the computer program. The heaters are either fully ON or OFF by constantly cycling their operation. The average power supplied to each heater may therefore be continuously varied. The temperature output is monitored along the tube via 2 sets of 32 thermocouples are located along the tube wall and the axial thermocouple probe(to monitor the combustion temperature). The thermocouples, type K (NiCr / NiAl) are connected to the data acquisition cards via compensating cable, then, linked to the computer.

Fig 3.10 Photograph of High Pressure Shell

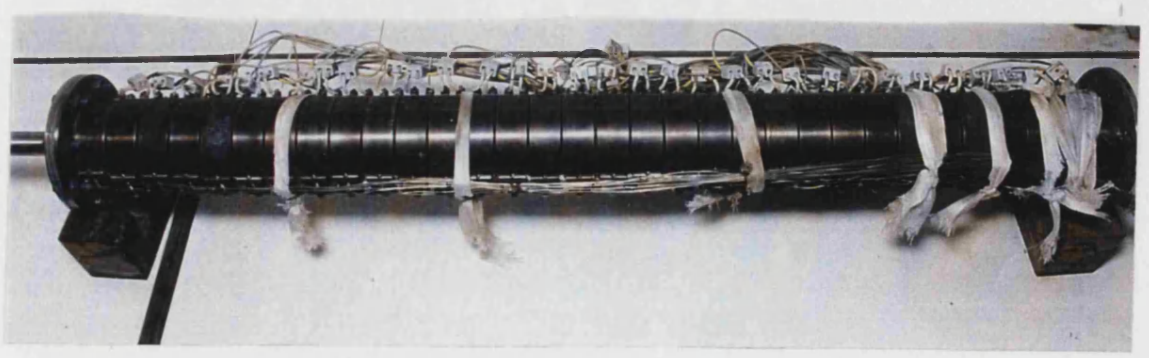


Fig 3.11 Photograph of Combustion tube

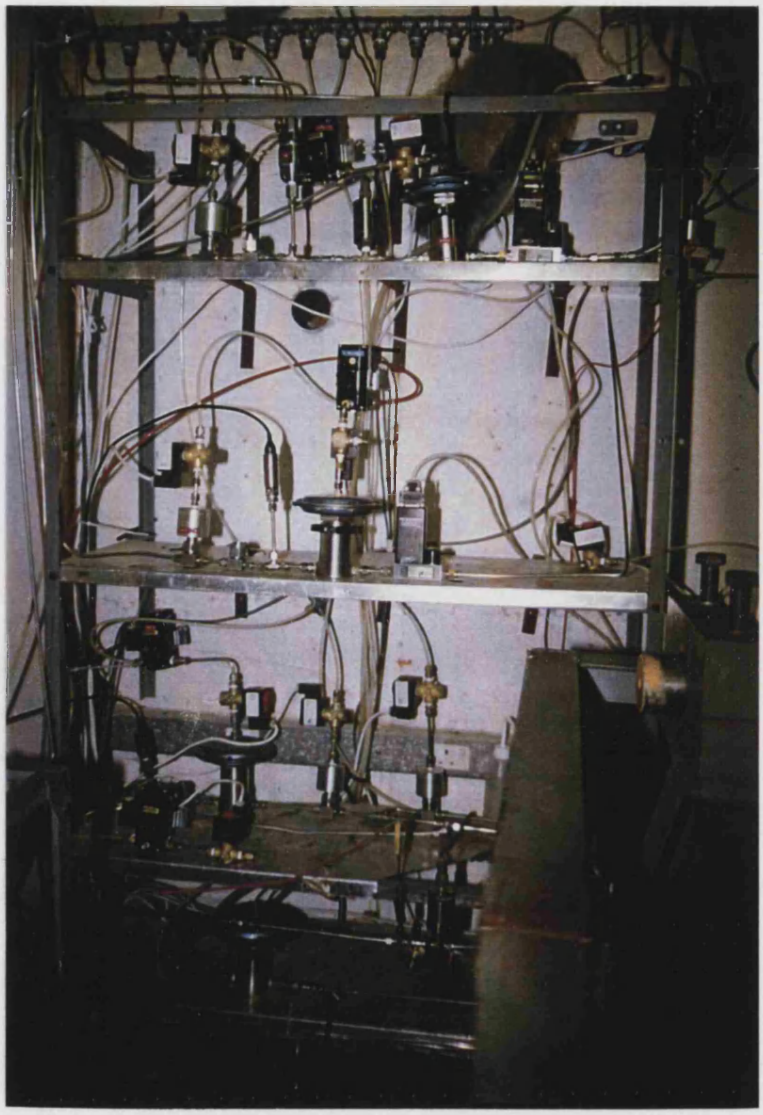


Fig 3.12 Photograph of the Gas injection system

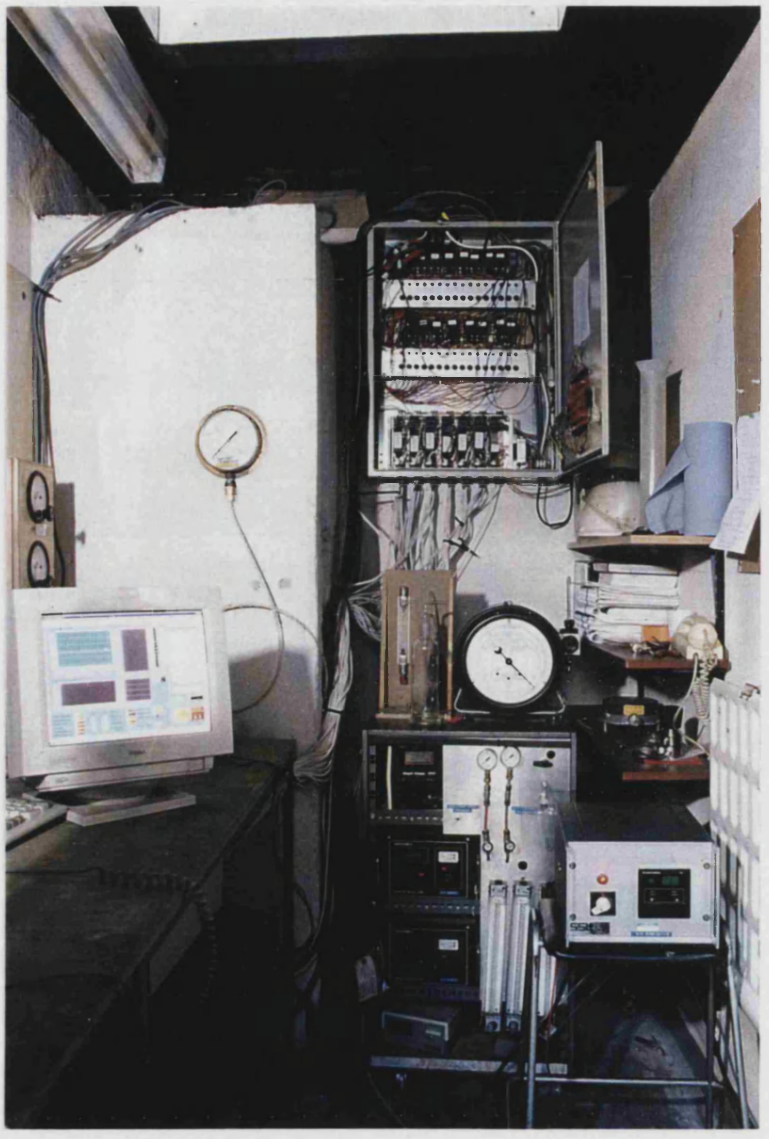


Fig 3.13 Photograph of ISC tube control system (in the observation room)

Fig 3.14 Photograph of Gas supply system

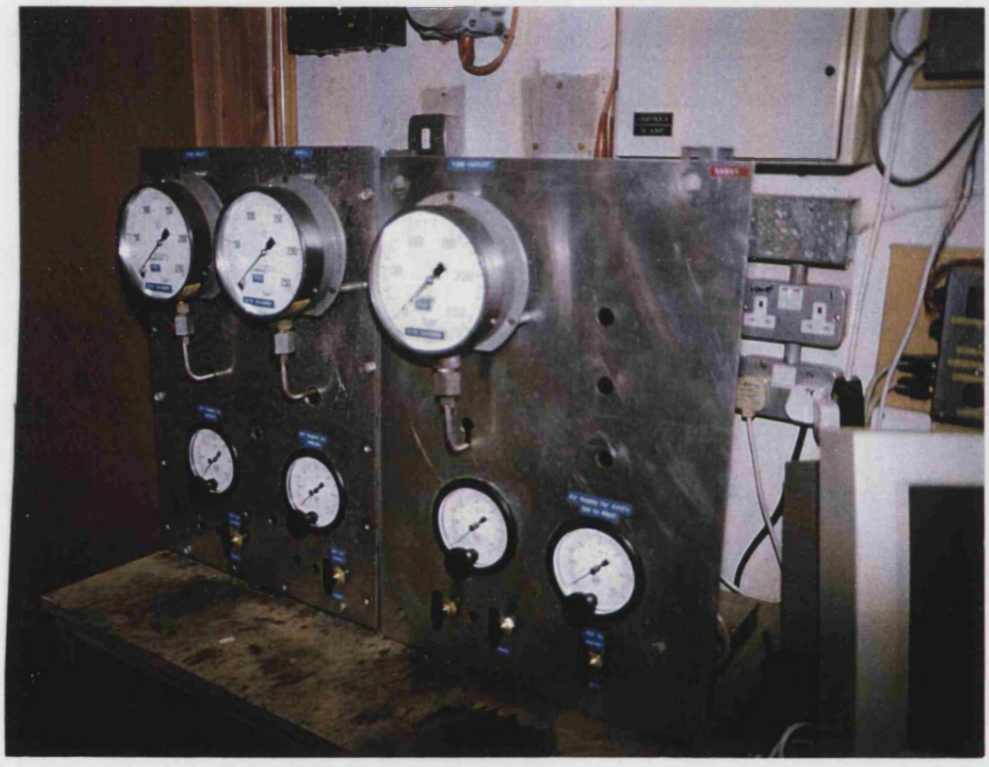


Fig 3.15 Photograph of the manual control station

CHAPTER FOUR

COMMISSIONING OF THE COMBUSTION TUBE FACILITY

Experimental procedure

4.1 Equipment preparation

Prior to running a combustion tube experiment, a series of preliminary checking and preparation procedures are required in order to ensure that all parts of the equipment are in perfect working order. Sufficient gas cylinders should be in place, and all should be full and connected to the injection lines. Inlet and exit lines are flushed using a small quantity of solvent (Jizer) followed by flushing with water to remove any traces of organic material, or dirt, then blowing through with nitrogen to dry all the lines.

The mass flow controllers need to be checked and calibrated to the required operating pressure and flow rate. All electrical and electronic equipment (SV`s, CPC`s, PPRV`s) should be checked and turned on for sufficient time. All measurement devices, such as pressure transducers, thermocouples, level detectors and gas analyser need to be in perfect working order.

4.1.2 Preparation of sand pack

The type and grain size of the sand to be used as well as the additives required (e.g. clay) are chosen to simulate the reservoir conditions in terms of porosity, permeability and matrix material. To obtain the right grain size, the bulk sand is vibrated for 30 minutes on a set of dry sieves (30, 54, 60 B.S). It is then weighed and mixed with clay (if required).

According to the tube volume ($0.00982m^3$), a mass of sand, oil, water and clay is mixed together . The volume of input oil and water varies from run to another depending on the required porosity and saturation. The sand mixture, oil and water requirements are given in Appendix (A).

In order to simulate a water wet reservoir, the sand and kaolinte mixture is first mixed with water and then left one hour to ensure uniform wettability. The oil is then added in small amounts and thoroughly mixed.

The mixture is kept in a covered plastic container in order to minimise any evaporation before introducing it into the combustion tube.

4.1.3 Combustion Tube Preparation

Before installing the tube into the pressure shell, the following checks must be carried out :

First, verify that all of the wall thermocouples are in place, with each thermocouple held in place next to its associated band heater. The securing screws should be tightened only to finger tight. Then verify also that each band heater is working correctly. Check any damaged wires due to excess heating. The bottom flange of the combustion tube should be bolted into position using a high temperature gasket for each run. A torque wrench should be used to tighten the six flange bolts to 60 Nm. Making sure that the bolts heads face away from the tube with nuts on the inside and washers on both sides. Heat resistance super sealant (silicone rubber, Dow Corning Type 3145) may be used to ensure good sealing

4.1.4 Installing the Combustion Tube into the Pressure Shell

First, the packing is removed from the stuffing box on the bottom flange of the pressure shell. A Sindanyo insulation block is used to prevent heat transfer from the end of the combustion tube to the shell body. This is lowered by a wire until it rests on top of the bottom flange of the pressure shell. The combustion tube is then inserted into the pressure shell, ensuring that the tube rests on the 'Sindanyo' block and the exit line passes. Piston 'V' rings are then slid on to the exit tube (the thinnest first and lastly the thickest) and finally stuffing box cap is bolted on.

The shell should then be lowered to a 45° angle using the small crane, and the axial thermocouple probe is inserted through the tube. A mesh filter is slid down along the axial thermocouple probe, to rest on the bottom of the tube. This is used to prevent sand entering the production line. It is very important to make sure that the filter is undamaged before lowering it down.

4.1.5 Placing Sandpack in Combustion Tube.

A Plastic bin liner is first taped over the combustion tube top to prevent any spillage entering into the shell annulus. The mixture is then fed into the tube in 0.75kg amounts at time. Special packing tools or tamping rod, is used to ensure uniform packing of the sand pack. A small amount of pure linseed oil is poured on to the top of the sandpack around the ignitor. This is used to aid ignition. Remove the plastic bin liner and clean the top flange and bolts holes of any oil and sand. Bolt into position the combustion tube ignitor flange and torque each bolt to 60 Nm. Fill the pressure shell annulus with vermiculite insulation, overflowing the top flange by a couple of centimetres. Connect the band heater wiring first, followed by the wall thermocouples and then the igniter connection. Lay the wiring carefully around the tube inlet so that they do become caught when the shell top flange is put in place.

4.1.6 Shell Positioning.

The pressure shell and the tube assembly is transferred from the laboratory to the bunker (safety cell) on a special designed track. Using the beam crane, slowly lower the top shell flange into position. Insert the flange bolts head down and screw on the nuts from the top with full washers on top and washers with cut away edge underneath. A torque wrench is used to tighten the flange bolts to 12.5 Nm.

Lower the shell carefully into the safety cell. Connect all pipe work, along with band heater and thermocouple wiring. The earth wiring of band heaters and igniter must be connected to a special point on the tube inlet line.

4.1.7 Safety Precaution.

Prior to performing a combustion tube experiment, several safety actions must be taken. First, inspect the emergency control panel air supply to see that this is working, then activate the ventilation fan from the switch in the main laboratory opposite to the side of safety cell. The roof-hatch must be then secured and a 'NO ADMITTANCE' sign must then be posted near the safety cell.

4.1.8 ISC Experiment Operation

When all the previous preparation of the combustion tube has been completed, the system is ready to run an experiment. This is started by running the LAB.VIEW-ISCTUBE.LLB software on the computer. A set of last orders will show up on the screen in the following sequence:-

1. Open gas supply to both tube and shell injecting lines.
2. Turn on the air compressor, make sure you get 80 psi operating pressure.
3. Plug in the band heaters power supply.
4. Plug in solenoid valves (SV),current converter (CPC), relay boxes and the rotating sampler power supply.
5. Put mass flowmeters on 'run -auto' mode.
6. Ensure air supply for emergency control station.

By completing the set of last orders, the system is ready to run the experiment. The next action is to press the OK button to start the run. The experiment starts by sending instructions to the data acquisition and SCXI box connected to the combustion tube equipment. The whole process can be summarised as follows:

Nitrogen flow to the tube and pressure shell injection lines is activated to build up the pressure to 10-15 bar above the operating pressure (e.g. 50, 75,100 bar). The computer will activate both back pressure and the tube and shell differential pressure sub-programs to hold the pressure and keep the difference between tube and shell within 2 bar. When the required pressure is reached, the computer program stops injecting gas, and activates the band heaters to raise the system temperature to the required reservoir temperature. The igniter is kept on until ignition is confirmed.

When the ignition temperature is reached, the exit gas line is opened to drop the system pressure by 10-15 bar to the normal operating pressure and to create pressure differential across the mass flowmeters to enable them to work at the required pressure.

As soon as the correct pressure differential is achieved, the flowmeters should start immediately delivering air or enriched air into the system at the desired flow rate. The time when injection of air or enriched air starts is considered to be the zero time of the experiment. Ignition is observed on the computer screen when there is a rapid increase in the zone one temperature measured by the axial thermocouple. This should also be associated with decreasing oxygen and increasing carbon dioxide in the exit gas. At this point band heaters must be put on adiabatic mode to control heat loss from the tube. Combustion front propagation is observed throughout the tube by regions increasing in temperature to a maximum and then decreasing as the combustion front passes. All of the measurements involving the process such as pressure, temperature, gas injection flow rates and produced gases composition (O_2, CO_2, CO) are stored on the computer hard disk. The produced liquids are collected automatically at the rotating sampler down stream from the low pressure separator.

The run is terminated when the last axial thermocouple reaches 200°C, or if an emergency occurs, e.i. tube plugging, too high tube and shell differential pressure, vent failure, computer program or power supply failure, or severe oxygen break through.

4.2 Commissioning of the Combustion Tube Facility.

Achievement of full commissioning of the combustion tube system is a vitally important stage of operation, which can confirm that all the equipment is working correctly. The commissioning process first involved testing all of the sub-component assemblies, e.g. , solenoid valves (SV), pressure transducers (Pts) and band heaters, secondly that all lines and connections were pressure-tight, leading to a full pressure test of the whole combustion tube facility. This was then followed by flow and pressurisation

4.2.1 Pressure testing of injection and production lines

All of the injection and production lines of the combustion tube were thoroughly cleaned with solvent (Jizer) to remove any traces of organic materials ,and then dried with air. The tube fittings and connection were then tightened. A dummy tube was used in place of the thin walled combustion tube to provide an extra measures of safety. The dummy tube was a thick walled stainless steel tube, 15.75mm and 8.5mm wall capable of withstanding up to 10,000psi. Air cylinders at 130bar supply pressure were connected to the oxygen and the nitrogen injection lines. The computer software 'Lab-View' was used to operate the control equipment through the library of VI control programs which includes; com.tube.DAQ.VI, Tube pts test.VI, pressure up test.VI, SV manual control.VI and pressure graph.VI. The control programs of the combustion tube facility are shown in flowsheet Fig.4.1. Full details of the software commissioning were reported by Young 1998.

At the start of the test, PT1 indicated a pressure of 130 bar, i.e. the injection pressure. Then PPRV1 was opened remotely by using CPC1 (current to pneumatic converter) to give 40 bar down stream PPRV1. The air flow rate was controlled by LMF1(oxygen mass flow meter). When AAV16 was opened, PT2 at the inlet of tube read 40 bar, allowing gas to flow through the tube ,and out through the gas

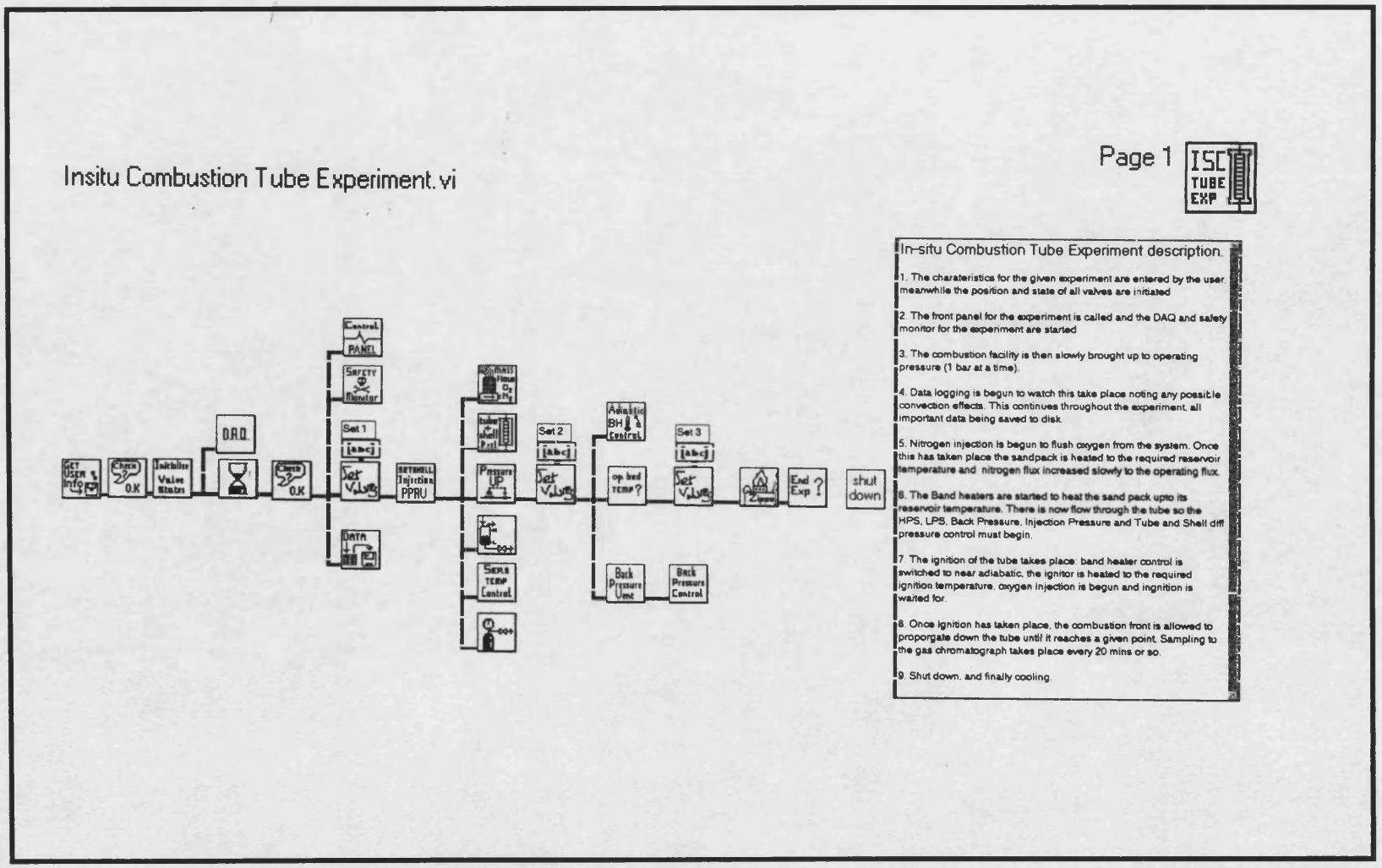


Fig. 4.1 Control Program for the operation of the Combustion Tube Facility

exit line, where PT4 indicated the same reading as PT2(40 bar). The AOFMF valve was operated by CPC7 and AAV20 by SV13 to control the system back pressure.
The liquid production line of the HPS was controlled by the valve V18 and AAV6. In this first test, the air was allowed to flow through PPRVL1 to PT5 which read 30 bar, the maximum inlet pressure of the LPS.
The pressure test was repeated at 70 and 100 bar in a smooth manner except for some minor leaks on tubing connections, which were subsequently tightened. The pressure profile for the system pressurisation commissioning can be seen in figures (4.2) and (4.3)

4.2.2 Dry Run under Cold Conditions

The main objective of this run was to achieve full commissioning of the gas supply and pressure control, using the actual combustion tube. The combustion tube was packed with sand (slightly wet) and then placed inside the pressure shell.

Control of Differential Pressure between the Combustion Tube and Pressure Shell

The combustion tube has a very thin wall (2mm),and consequently can not support any pressure above about 4bar, thus it is necessary to control the pressure difference between the tube and the shell to prevent the tube collapsing. In order to control the shell pressure and differential pressure simultaneously, air cylinders at 130bar were connected to both oxygen and nitrogen lines and the pressure shell injection line.
All of the test equipment was activated by using the subprogram Testing.LLB .

The test was started by pressurising the system up to 40 bar using the shell injection line. PPRV3 was opened remotely by using CPC3 via SV27. AAV22, AAV19 were turned on by using SV25 and SV26, respectively. This action enabled simultaneous air flow in to the shell and tube. Computer task 'Tube and shell D.P' (control test.vi) was used to control the differential pressure between the pressure shell and the tube.

The differential pressure was controlled at 1.2 bar maximum, whilst the back pressure on the tube was changed to 25,30,40 and 50 bar. As can be seen in Fig 4.4, the back pressure accurately adjusted to the new setpoint, whether increasing or decreasing, while at the same time maintaining a differential pressure of 0.5bar at the exit. Fig 4.5 illustrates the accurate level of differential pressure control achieved.

When the pressure reading of PT2 tube inlet , PT3 shell pressure and PT4 tube outlet all indicated the same value of 40bar, the valve AAV19 was turned off to terminate the supply of air to the combustion tube via the shell feed line. If the pressure in the shell was greater than the tube by more than 2bar, the software could send a signal via CPC to PPRV6, to vent the difference in pressure. The nitrogen injection line was used to increase the tube pressure to 70 and 100 bar. It was possible to control the differential pressure between the tube and shell to less than 2bar using this venting procedure.

Back Pressure Control Test

The main objective of the back pressure control system, is to maintain the required operating pressure for the experiment, i.e. back pressure on the combustion tube.

In order to achieve this, the system was provided with back pressure control valve AOFMV, which controls the pressure on the gas line from the HPS by the software program (back pressure control).

Full air cylinders were connected to the system, and air was injected through the nitrogen injection line to pressurise. the system up to 40 bar. The back pressure valve AOFMV was operated by the computer. However it was not possible to achieve the desired control of AOFMV, since the valve was acting simply in an ON/ OFF mode. A number of signals were sent to CPC7 between 4ma (fully close) to 20 (fully open), but no control improvement was achieved. After full investigation, the specification of AOFMV was found to be oversized. The valve coefficient (CV) was (0.06) which is too large for the duty required. AOFMV valve was replaced with a (PLATON, 'M' type) valve, but again the valve trim size was too large.

A new valve trim (P4), which had a CV of 0.00004 was installed. The position of the AOFMV valve was also transferred to the end of the gas exit line (after the LPS), in order to control the back pressure by controlling the whole amount of the system gas. Back pressure control profiles are shown in Figures 4-6 and 4-7.

Figure 4-6 shows excellent back pressure control using a constant gas flowrate 7 l/min, while the second graph illustrates the back pressure control using different air flux. It was noticed that, in Fig 4.7 the use of a lower gas flowrate (less than 2.5 l / min), caused the back pressure control to depart seriously from the required setpoints. Thus it is recommended to use an air flux greater than 2.5l/min for better pressure control.

Successful commissioning of the pressure shell and combustion tube differential pressure and back pressure was achieved under cold conditions with different flow rates and ranges of pressure up to 130bar. Depressurisation of the system through the emergency venting control was also accomplished.

4.2.3 Wet Commissioning Run

After a series of dry runs using both dummy and real combustion tube. A wet commissioning run with the real combustion tube was carried out using wet sand, air and liquid rates which were very similar to those required in of the in-situ combustion experiments. The main purpose of this run was to test the injection abilities and pressure control in the presence of a liquid phase, then to carry out precise commission test for the high and low pressure separators and the performance of the band heaters. The combustion tube was packed with water saturated sand and the axial thermocouple probe was installed. As it can be seen in Figure 4.8, excellence pressure control of the combustion tube was achieved, whilst the HPS and LPS were working.

Band Heaters Tuning

After connecting all of the band heaters and thermocouples, the computer program (adiabatic BH control.vi and BH tuning.vi), was used to operate the first 12 band heaters. The tuning procedure was started by selecting temperature setpoint and using different PID values to provide different pulses (0 to 20 mv), which resulted in changes in heater output. The temperature of each band heater was measured by its associated thermocouple, located on the wall of the combustion tube. Theoretically if the chosen PID values are correct, the heat output is optimal so that the setpoint temperature is reached in a satisfactory manner. After many trials, each band heater was tuned correctly using a signal pulse 0 to 7 mv. The temperature response of the band heaters, using the tuning task e.g BH#3 can be seen in Figure 4.9 .

HPS and LPS Commissioning Test

The purpose of the commissioning was to test the ability of the level detectors installed in each separator to work under conditions similar to the real combustion process, i.e. where multiphase flow is present for separation at high pressure and temperature. First, both level detectors were tested outside the separators by inserting them in a water container. In each case the 'High' and 'Low' level readings were achieved exactly when the liquid reached the detectors. The detectors were then put in the separators for testing.

Air was supplied through the main nitrogen injection line and controlled by LMF2 which can provide a flow rate up to 15 lit /min. Water was injected into the system by a pneumatically operated water pump. The liquid levels in both separators were monitored on the computer screen via the level display.vi program.

Air was injected through the main nitrogen injection line and the water supply line was connected to the outlet of the combustion tube line. The system was pressurised first to 50 bar, then air and water were introduced at different flow

rates ranging from 13 l/min to 3 l/min and 15 ml/min to 75ml/min, respectively. Faulty level liquid signals were obtained i.e. 'high' level light on when no liquid level was achieved. Water also went through the exit gas line without giving an indication of high level.

The main cause of the inability to control the liquid level was insufficial space inside the separators for liquid and gas to separate. Then, bubble dispersion occurred and covered the ultrasonic level detector, causing it to gave a wrong identification of the fluid phase. Another possible reason for their failure, was that level detectors were subjected directly to the inlet flow which caused them always to be covered with liquid. i.e. they were permanently reading a 'high' level state.

The ultrasonic level detectors were abandoned and replaced by new float detectors designed by Young 1997. As it can be seen in Figure 4.8, it was possible to monitor and control the liquid level in both separators, even at high water injection rates. In the high pressure separator as the liquid reached the 'high' level point-7, the computer opened the discharge valve AAV6 to deliver liquid into the LPS. As the liquid level dropped to 'low' level point-3, the valve was closed. This process was repeated many times according to the flow of liquid from the tube. The liquid Production rate could be also calculated from the liquid drained from the separator i.e. every division on the level graduation represents 5ml of liquid. The low pressure separator had the same assembly and worked on the same principal as the high pressure separator. Liquid drainage from LPS can also be seen in Fig.4-8

4.2.4 Final Commissioning Test

The main aim was to achieve a full commissioned state of the combustion tube facility using the same sand, oil and water saturations as those that would be used in the real combustion experiment at the required operating pressure.

Two full commissioning tests (Run 1 and 2), were carried out at 50 bar operating pressure. In both runs, a full pressure and adiabatic control was achieved. The new float type level detector worked correctly and the computer software provided excellence control capability.

RUN 1

Connectivity between the pressure shell and tube was experienced. This resulted in equalising in pressure in the shell and the tube, making it difficult to reduce pressure in the tube because it was always resupplied from the shell side. This problem was subsequently solved in the following runs, where a high pressure high temperature sealing material (Dow Type 3145 silicone rubber) was used on both top and bottom tube flanges.

The discharge valves on liquid lines from both separators (PPRVL1, PPRVL2) did not work properly at the beginning of the run, because they needed specific tuning for oil. It was difficult to vent the shell through PPRV6, because the shell vent line became blocked with Vermiculite insulation material due to poor positioning of the vent line. This method was solved by repositioning the vent line on the top of the shell faraway from the Vermiculite insulation in the main body of the shell. Figure 4.10 shows the pressurisation and heating stage. The operating pressure was first built up to 58 bar, then the back pressure and the band heaters control were activated ,simultaneously, to maintain the operating pressure and heat up the sandpack to the required reservior temperature. The first peak of temperature around 80C represented the reservoir temperature, while the second peak up to 200C was the heat output from the ignitor.

Run 2

It was not possible to operate some of the band heaters(3,6,9, and 24,27,30) due to faulty wiring connections.

Run-2 would have been completely successful if gas pressure regulator PPRVG2 on the low pressure side had not failed to release the excess gas out of the system. This resulted difficulty in controlling the back pressure and gas injection rates, causing the run to be terminated. The Pressure up and heating performance for Run 2 can be seen in Fig. 4-11.

Final Modification to the System

Many modifications were made to the system, by replacing parts which proved incapable, or modifying some complex components in order to make them simpler. These modification are summarised as follows:

1. The main gas feed lines were reduced from 6 lines to only 4 lines. This are oxygen and nitrogen lines to the tube, nitrogen line to the shell, and the nitrogen dilution line. Gas feed lines to the manual control station have been reduced from 3 to only one . All theses lines were labelled and gas supplies identified.

2. A new PPRVL1 (pressure precision regulator liquid valve) has been installed on the exit liquid line from the HPS.

3. Complete new parts for the back pressure regulator PPRV8, and an air activated valve were installed just behind the pressure regulator.

4. All of the gas and oil production lines from the HPS to the LPS were rebuilt, in order to shorten the distance and time that products take from HPS to the collecting points. This created some extra space which was needed in the small safety cell.

5. A new AOFMV valve (PLATON, type- M, trim size: P2, CV= 0.00004) was installed on the gas production line from the HPS, to control the back pressure.

6. Of major importance, new HPS and LPS were built and fitted with new float type level detectors (details can be found under the HPS and LPS commissioning test, section 4.2.3)

7. A new gas manifold was built to distribute gas from the high pressure gas cylinders. Every line is provided with 2 two way valves, so that every line can be fed from two different rows of cylinders.

8. The state of every solenoid valve is monitored by 38 small lamps on the control panel. When the computer program is running , the lights can show the position of every SV, whether it is 'on' or 'off '.

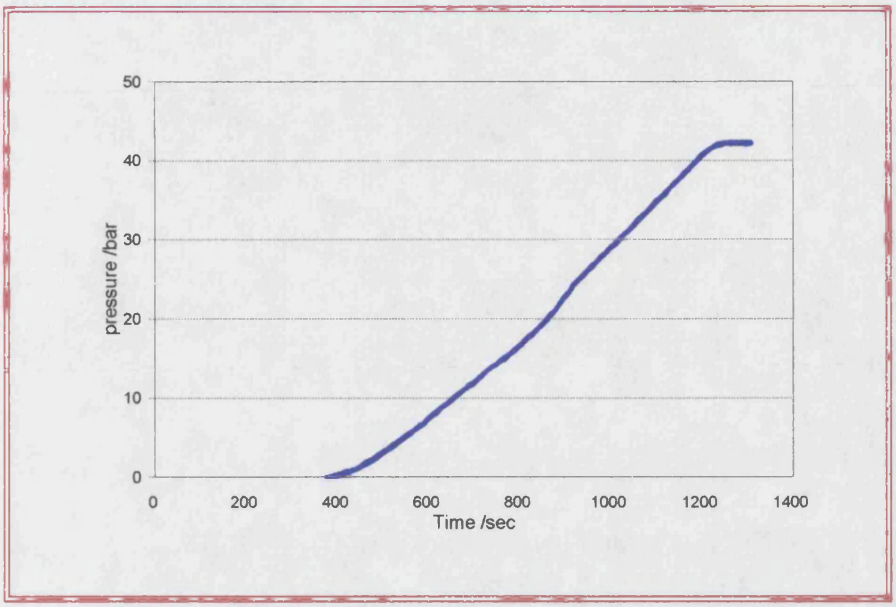


Fig. 4-2 Pressurisation of the Inlet and Production lines ['Dummy' Tube in-place]

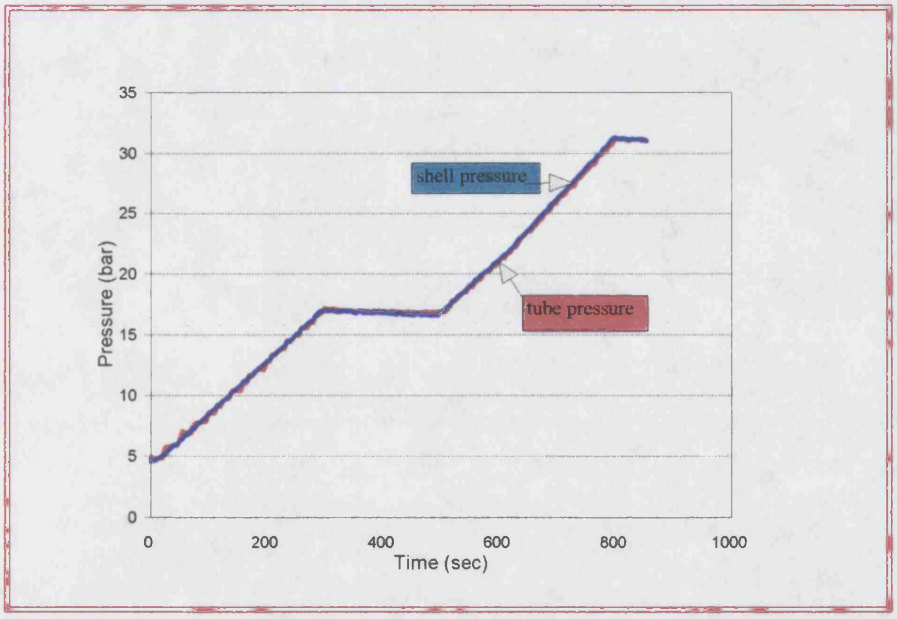


Fig. 4 -3 Simultaneous Pressurisation of Pressure Shell with 'Dummy ' Tube.

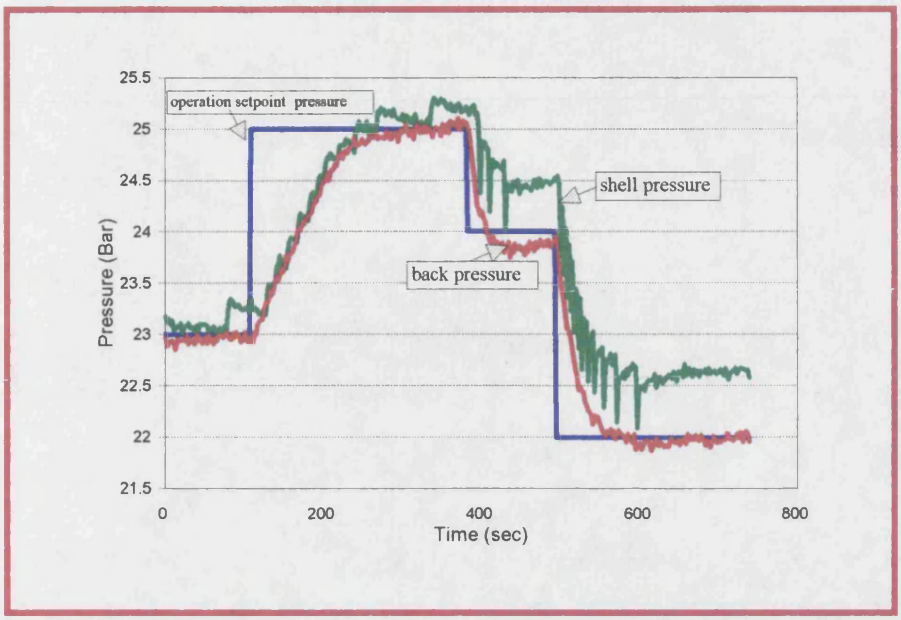


Fig. 4.4 Pressurisation of pressure Shell and Combustion Tube

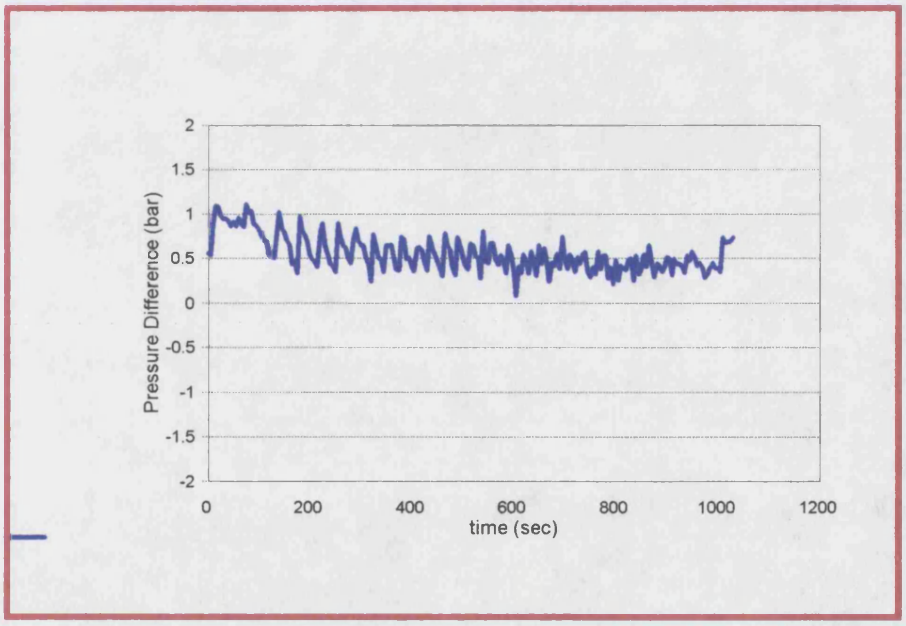


Fig. 4.5 Differential pressure control at 50 bar back presure

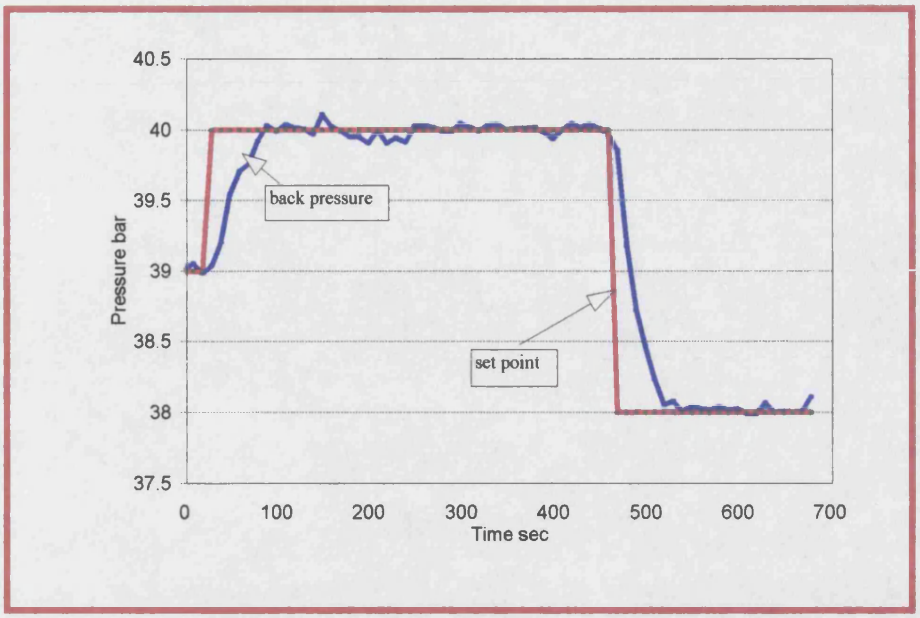


Fig. 4.6 Back pressure control at a fixed gas flowrate

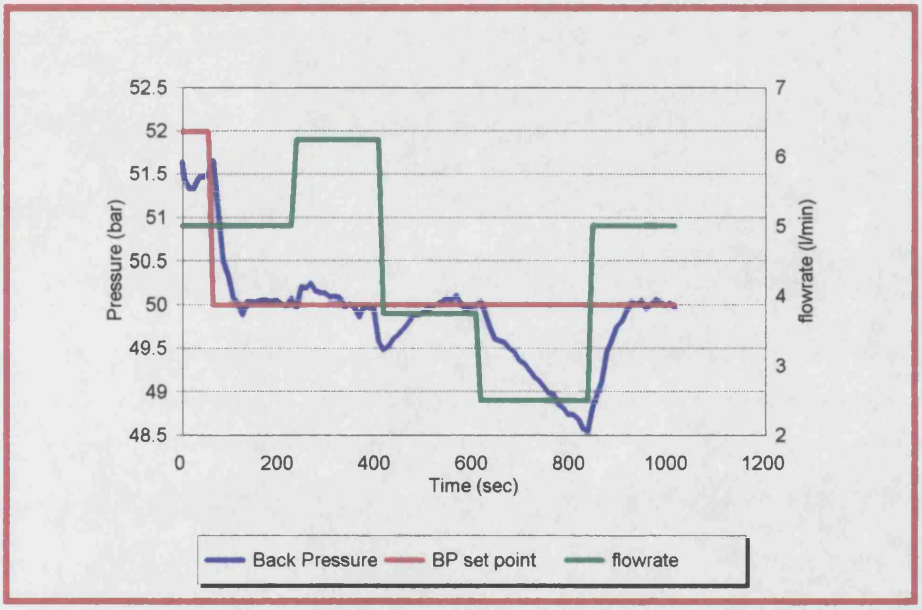


Fig. 4.7 Back pressure control at different gas flowrates

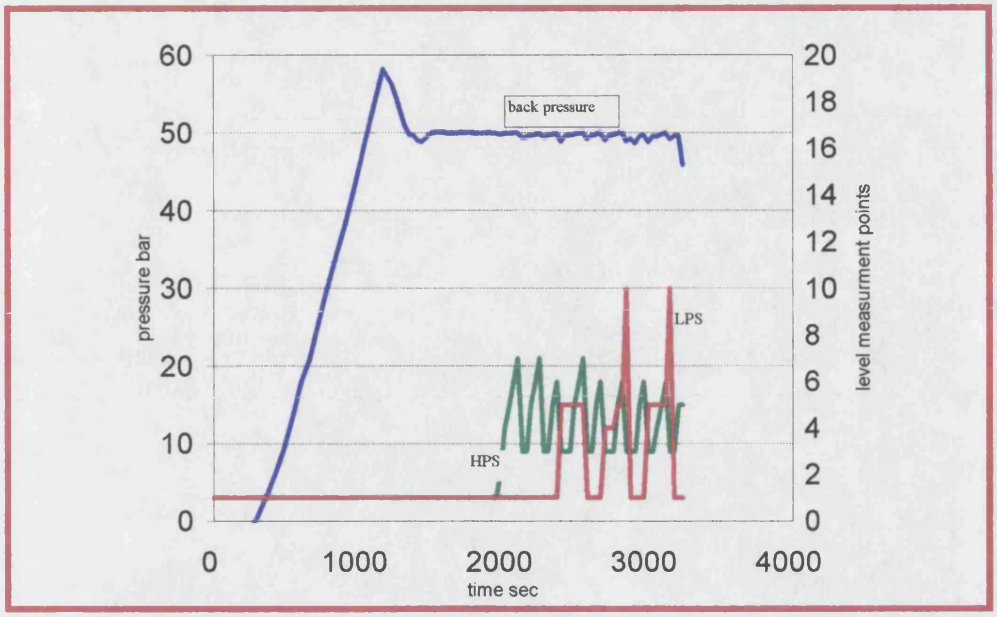


Fig. 4.8 Commissioning of the high and low pressure separators

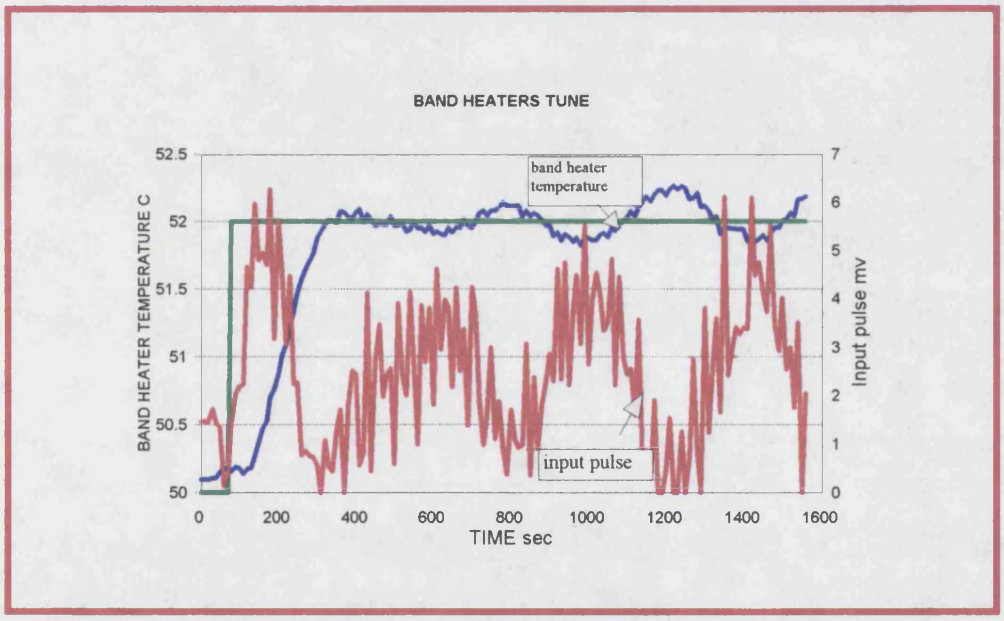


Fig. 4.9 Band heater tuning

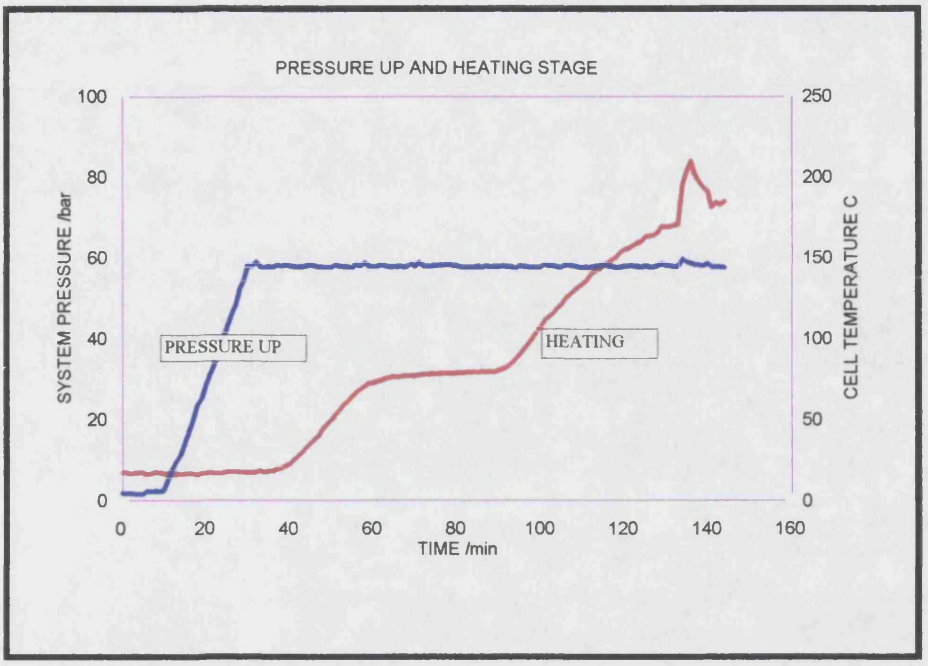


Fig. 4 .10 Final commissioning test Run-1

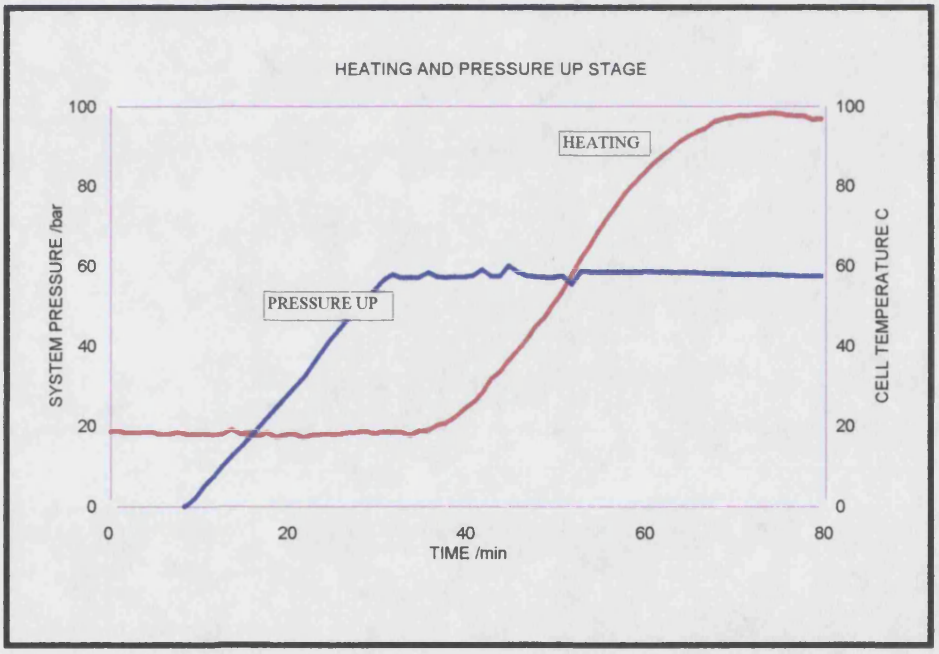


Fig. 4 .11 Final commissioning test Run-2

CHAPTER FIVE

RESULTS AND DISCUSSION

Experimental Results

Six experiments in total were performed all using air. Runs 3 to 6 used medium heavy Clair crude oil and run 7 and 8 used a much lighter Australian cruide oil. All these experiments were designed to simulate a water- flooded state, where there was a high initial water saturation, ranging from around 35% for the Clair oil to 50% for the Australian light oil. The results for each experiments are presented separately, so as to identify particular features associated with each run. The initial sandpack properties and operating conditions for each experiment are listed in tables 5.1 and 5.2.

Table 5.1 Initial conditions of Combustion Tube Experiments

RUN	3	4	5	6	7	8
Sand type	Coarse W 50	Coarse W 50	Fine W150	Coarse W 50	Coarse W50	Coarse W50
Sand weight %	90	90	90	90	90	90
Clay weight %	10	10	10	10	10	10
Porosity %	36	36	45	36	36	36
Permeability md	1004	1004	616	1004	1004	1004
Crude type	Clair Medium oil	Clair Medium oil	Clair Medium oil	Clair Medium oil	Australian. Light .Oil	Australian. Light.Oil
Gravity API	19.8	19.8	19.8	19.8	38.78	38.78
Density kg/m3	935	935	935	935	828	828
Oil saturation %	60	60	48	60	41	45
Water. saturation . %	35	35	28	35	50	50
Gas saturation%	5	5	24.3	5	9	5

Table 5. 2 Experimental operating conditions

Run	3	4	5	6	7	8
Combustion mode	Dry	Dry	Dry	Dry	Dry	Dry
Operating pressure bar	50	50	75	100	70	70
Bed temperature °C	80	80	80	80	63	63
Air Injection flux: m3/m2.hr	50 -75	20	60	60	30 - 100	20 - 8
Injection gas	Air	Air	Air	Air	Air	Air

5.1 Medium Heavy Oil Experiments

Run 3

After an extensive and successful commissioning tests, the system was ready to carry out a full high pressure in-situ combustion experiment. Run 3 was the first full in-situ combustion experiment performed at 50 bar pressure with Clair oil.

The experiment was started by pressurising the system to 60 bar and raising the sandpack temperature to 80C (reservoir temperature). The igniter was turned on for 40 minutes, but the temperature in the first zone of the combustion tube only achieved 220C. This was because the thermocouple in this zone was not close enough to obtain the correct igniter temperature. The decision was taken to start injecting air as the temperature around the igniter was in fact likely to be much higher than what was actually observed.

The system pressure was brought back to 50 bar with a 10 bar differential pressure required across the mass flowmeters. The period of pressurisation and heating of the sandpack took 1.5 hours as can be seen in Figure 5.1 and 5.7

Ignition took place after 17 minutes from starting air injection. 10 minutes following ignition, the combustion temperature reached 750C. The experiment was designed for a flux of $50m^3/m^2.hr$, but this could not be achieved precisly owing to difficulty in to control the back pressure via the exit gas control valves (PPRVG1, PPRVG2)

This affected both of the mass flowmeters, causing them to deliver more gas into the system, with range 50 - 75 m^3/m^2hr.

As it can be seen in Figure 5.7, the temperature profile contains two peaks. The first one lasted about 28 minutes following ignition, achieving a maximum temperature of over 800 °C averaging 650°Cover the period. In the next 25 minutes, the temperature gradually reduced as the percentage of oxygen fell from 21% to 12% due to the mass flowmeter malfunction described previously. The second temperature peak appeared after the correct oxygen composition was restored, with maximum temperature of over 700°C. The experiment lasted 72 minutes in total and was terminated when the last two thermocouple readings reached 200C. Figure 5.25 shows the development of the temperature profile through the tube on a function of combustion time

The gas profile in Figure 5.13, shows that oxygen was completely reacted during the experiment with very little, if any low temperature oxidation (LTO) occurring during the initial combustion period. The produced values of CO and CO_2 averaged of 13% and 3% respectively.

The results and parameters for the experiment, together with those for all of the experiments, are summarised in Table 5-3

RUN 4

This run was intended to repeat the same design gas flow as run 3 (50 m^3/m^2hr), but was in fact done using a much lower flux (20 m^3/m^2hr) than run 3, owing to a gas leak in the system. The same sandpack properties as for run 3 were used.

Pressurisation and heating-up the sandpack as shown in Fig 5.2 and 5.8 took exactly one hour. Air injection was started with 50 m^3/m^2hr, but a gas leak on the top of tube reduced this to only 20 m^3/m^2hr. The ignitor reached 400°C, but combustion was not initiated until 20 minutes after starting injection. To achieve this, the oxygen composition was increased to 40% to enhance the combustion. As soon as combustion was achieved, the temperature rose to 500C, and the CO_2 and CO levels increased rapidly. The oxygen level was immediately reduced back to 21%.

As it can be seen in Fig 5.8, the combustion process progressed very steadily for 105 minutes, achieving an average combustion temperature of 460°C. Almost completely oxygen utilisation was achieved, and the CO_2, CO levels were steady at an average of 15% and 4%, respectively. The temperature profile development is shown in fig 5.26.

RUN 5

The use of low injection flux of 20 m^3/m^2hr in Run-4, demonstrated that there was a high capability to sustain combustion. Run 5 was designed to use a higher flux of 60 m^3/m^2hr to investigate the process performance at the high flux level. The other difference in this run compared to run 3 and 4 previously, was the use of lower initial oil and water saturation and a fine grade of sand (W150) for the sandpack.

The first trial of this experiment failed after one hour, during the heating up stage. This was due to a gas leak in the tube exit line. The run was shut down to repair the leak, and then resumed starting from the point where it was terminated. Fortunately, the system did not loose pressure. The pressure profile during the run is shown in Fig 5.3. Air injection started 19 min after resuming the second trial, at a total rate of 60 m^3/m^2hr. Combustion was initiated 33 minutes after air injection, achieving an average combustion temperature of around 600C. Initially the produced gas and temperature profile Fig 5.9 was divided into three zones (A,B,C),according to the development of process. In Zone A, the combustion propagated steadily for 28 minutes with an average combustion temperature of around 600°C and high oxygen utilisation (around 90%). The CO_2 and CO levels in produced gases increased steadily up to 9% and 4% respectively. By the end of this short high temperature period, oxygen in produced gases had increased to7% and was associated with a rapid decrease in the combustion temperature to around 400C. This occurred, because during the first period of combustion , the sandpack had became desaturated down stream of the front, and hence there was not enough fuel available to consume all the injected oxygen. This region can be clearly seen in Fig.5-9 of temperature profile section labelled B. As the combustion front reached more fuel down stream (Zone C), combustion became more efficient, achieving full oxygen utilisation. However, the

combustion temperature did not increase to its previous level. This phenomenon can be more clearly understood from the post mortem analysis which showed, that the combustion front had deviated from the centre of the tube towards one side of the tube. This left a clean unburned sand around the axial thermocouple, i.e. unswept by the combustion front. This means that the combustion temperature observed in zones B and C may not represent the correct combustion temperature. It is estimated that in these zones in Fig 5.9, the temperature should be much closer to what was observed in Zone A .

RUN 6

The main objective of this run was to study the combustion performance at 100 bar. The experiment was started by pressurising up to 100 bar and heating the system to 80 C, as shown in figures 5.4 and 5.10. This stage took 83 minutes, before air injection flux was initiated at 60 m^3/m^2hr. After a further 24 minutes ignition was first observed and combustion propagated steadily for a further 247 minutes, achieving a maximum temperature of 504C, (averaging 463C).

The oxygen utilisation was 91% during the most steady period of combustion (70 to 87 minutes from ignition), and around 77% the overall run. The CO values ranged between 3% and 6% while the CO_2 values averaged 15%.

As it can be seen in Fig 5.10, the first period of combustion peak lasted 129 minutes following ignition. Following this the temperature as well as CO and CO_2 started to decrease and the oxygen level in exit gases increased up to 7% . This effect is the same as was observed in Run-5, lack of fuel to consume the whole injected oxygen as result of oil desaturation down stream of the front. As the combustion front advanced into more fuel in region down stream, the combustion temperature stabilises again along with increasing of CO_2 and CO levels.

The Run was terminated after 247 minutes, when no more oil was produced The experimental parameters measured are summarised in Table 5-3 .

5.2 Light Oil Experiments

The success obtained with the medium heavy crude oil (Clair 19.8 API) provided encouraging basis to do some experimental work on a light crude oil at high pressure.. The main objective therefore was, to **first,** test the system capability to operate with a light oil and to know what modifications might be needed, and **secondly,** to study the feasibility of light oil in-situ combustion at high pressure, where a higher residual fuel content may exist to sustain combustion.

RUN 7

The aim was to investigate the feasibility of air injection into light oil reservoirs. The sandpack and oil properties are given in Table 5.1 The initial oil saturation at 45% in the sandpack, was lower than that used for Clair oil studies. The initial water saturation was also significantly higher at 50%, which is typical of a well swept water flooded region in a light oil reservoir.

The run was designed for a flux of 30 m^3/m^2hr, however, this flux was right for 42 minutes following ignition (see Fig 5.5 and 5.11). However a fault in the mass flowmeter operation failed to deliver the correct flux, causing it to increase to a very high value of 100 m^3/m^2hr. As can be seen in Fig 5.29, the main feature of this light oil 'ISC' experiment, was that a fully propagating reaction was sustained at a temperature of only 255C. Then the process was not high temperature in situ combustion, rather it was high flow LTO. Although, the process eventually stabilised towards the end of the run, the major part of experience was high levels of oxygen production. The experiment lasted 145 minutes and swept out 64% of the tube length.

RUN 8

Since Run-7 was performed at a high flux and for the most part did not achieve stable temperature or high oxygen utilisation, the main objective was to use a much lower flux to stabilise the performance. The experimental conditions were of the same as those used for Run 8.

The run was started with injection flux of 20 m^3/m^2hr. Because of a fast oxygen breakthrough (the oxygen in exit gas increased to 10.3%), the flux was reduced to 15, then to 12 and finally to 8 m^3/m^2hr. The peak temperature then became much more stable at 250C. The oxygen utilisation improved to 94% and the CO_2 and CO levels increased to 8% and 1.5% respectively. A after 5.5 hours, the process began to die-away as the fuel availability decreased. However, the injected oxygen was still completely consumed to produce CO and CO_2 as shown in Fig 5.12

Table (5 - 3) Summary of Experiments results.

Run	*3*	*4*	*5*	*6*	*7*	*8*
Crude type	Clair	Clair	Clair	Clair	Australian Light oil	Australian Light oil
Gravity (^{0}API)	19.8	19.8	19.8	19.8	38.78	38.78
Pressure (bar)	50	50	75	100	70	70
Air.Flux (m3/m2.hr)	30 - 75	20	60	60	30 - 100	20 - 8
Temperature ^{0}C	700	460	600	450	255	250
CombustionFront Velocity (cm/hr)	14.4	11.2	15.3	20.2	31	16.3
Combustion time (min)	72	115	93	247	155	330
sweep % of tube length	19	18	26	56	64	68
CO2 %	13	15	10	15.2	6.4	6.5
CO %	4	4	3	5	1.2	1.4
O2 Utilization %	98	96	96	91	29 to 90	42 to 94
Oil recovery (%OOIP)	39.8	35.6	40	83	43	64
Water recovery %	14.3	6	7.7	58	41	42
Fuel burnt(%OOIP)	3.1	1.56	3.2	9.5	4	2.3

5. 3 *DISCUSSION OF RESULTS*

5.3.1 Combustion Temperature

The combustion temperature performance in the sandpack is monitored by 32 axial thermocouples contained in the axial thermocouple probe, which extends along the tube. The temperature measured by the first two thermocouples is affected by the ignitor, so that artificially higher combustion temperatures are obtained initially. The temperature measured by succeeding (downstream) thermocouples will steadily rise as the combustion front approaches, and then gradually decrease as the front passes by.
The combustion front is located from a plot of the maximum temperature measured by each thermocouple against distance (the combustion tube length).
Table 5.4 shows the main results concerning combustion peak temperature and combustion front velocity for the medium heavy and light oil experiments.

Table 5. 4 Combustion Temperature, Front Velocity and Sweep

Run		*3*	*4*	*5*	*6*	*7*	*8*
Crude type		Clair medium oil	Clair medium oil	Clair medium oil	Clair medium oil	Australian Light oil	Australian Light oil
API Gravity		19.8	19.8	19.8	19.8	38.78	38.78
Operating pressure (bar)		50	50	75	100	70	70
Air Flux (m^3/m^2hr)		60 - 75	20	60	60	30 - 100	20 - 8
Pressurisation and heating-up stage (minutes)		105	84	94	104	60	111
Combustion temperature C /	**peak**	804	500	670	503	320	257
	avg	700	460	600	450	255	250
Combustion Front Velocity (cm/hr)	**max**	21.7 max	13.5	22.2	25.7		18.2
	avg	14.4 avg	11.2	15.3	20.2	31	16.3
Combustion time (min)		72	115	93	247	155	330
Combustion front sweep (% of tube length)		19	18	26	56	64	68

Generally the pre-combustion stage (pressurisation and heating of the sandpack), took between 1 and nearly 2 hours for all runs. For the Clair oil, ignition took place about 20 minutes after the start of air injection, whilst for Run-7 (light oil), ignition took 33 minutes. In this latter case, this longer time was because of the high flux, which caused oil desaturation around the ignitor zone. In run-8 (light oil), ignition took only 10 minutes to occur, indicating that there was no oil desaturation occurring at the lower air injection rate.

As shown in Table 5.4, Runs 3 to 6 conducted on medium heavy Clair oil achieved a high temperature combustion mode combustion (HTO) in all cases with average peak temperatures of 460 to 700C. The combustion temperature profiles for each run are given in Figs 5.7 to 5.10. All exhibit some variability in the peak temperature, especially Run 3 and 5. Run 4 achieved the most stable profile, whilst Run 6 stayed within the range of 400 to 500 C.

Runs 7 and 8 on the light Australian oil produced a different combustion performance compared with the medium heavy oil runs. The average peak temperature was only around 250C, although it did reach as high as 330 C in Run-7, temporarily, before dedining to 220C. The high temperature was obviously due to the much higher air injection rate , but this could not be sustained. The process generally can be considered to be one of low temperature oxidation (LTO), rather than high temperature oxidation or combustion .

5.3.2 Combustion front movement

The combustion front advancement is very much dependent on the amount of fuel available for combustion, when more fuel is available, it will take longer to burn, hence slowing the advancement rate of the combustion front(**Alexander et al 1963**). It was noticed in all runs that, the combustion front velocity in the early periods was relatively slow, but then became faster as the combustion propagated further down the tube. This can be explained by more fuel being available at the beginning of the run, but as the combustion became established more oil is either produced or displaced down stream. Thus with less fuel formed because of oil desaturation ahead of the combustion

front, the combustion front velocity increases significantly. This can be seen by comparing the front velocity in Run 3 to 6 in Table 5.4. They are 14.4 cm/hr and 20.2, respectively. This because more fuel was available in Run-3, leading to high combustion temperature and slower rate of combustion front advancement.

The peak temperatures and combustion front movement in all runs looked very similar following the trend of fuel availability along the sandpack. In Figure 5.7 (Run-3), there are two temperatures peaks occurring at about 1.8 and 2.2 hrs. The slow temperature decline is the result of oil desaturation ahead of the front due to gas stripping and vaporisation. It is not really a sudden 'jump' effect, but rather is more gradual drainage and as the fuel availability downstream increases again, so that the temperature begins to increase. The situation is similar in Run-5, where two temperature peaks at 0.6 and 1 hrs were observed (Figure 5.9, Zone A). Lack of fuel reduced the combustion temperature to 420 C in the following region. However, the combustion performance improved noticeably down stream (in Zone C), as both the oxygen utilisation and CO_2 increased rapidly. The temperature in Zone C, did not represent the correct combustion temperature, because the combustion front was deviated away from the axial thermocouple. In run-6, the effect appears a little more complicated. Interestingly, Run 6 shows a long stable period between 4.2 and 5.8 hrs, and the temperature stars to pick up again near the end of the tube where, normally, one expects to see a declining oil saturation. Auto ignition down stream of the combustion front or 'skipping phenomenon' did not appear to happen with both medium and light oil experiments.

The combustion temperature profile Fig. 5.28 (Run6 with Clair oil) shows a definite steam plateau region, which became less defined in the middle part of the tube, but later became more stable, extending for nearly one third of the tube length. In the light oil experiments, the steam zone was less definite due to the low temperature achieved.

5.3.3 Effect of Air Injection Flux.

Comparing Run 3 and 4 on Clair oil, high air injection flux resulted in higher combustion temperature and higher combustion front velocity, as shown in Table 5.5. As the total injection flux decreased from (60-75) m^3/m^2hr (Run-3) to only 20 m^3/m^2hr (Run-4) (Figs 5.7 and 5.8), the combustion temperature reduced from 700C down to 465C (average) in Run 4 at the lower injection flux. Correspondingly, the combustion front velocity was reduced down to11.2 cm.

For the light oil Runs 7 and 8, the use of high flux caused the combustion temperature to reach 330 C at the beginning of Run 7, Figure 5.11, although this could not be sustained because of the oil desaturation ahead of the combustion front. Following to this period, the use of high flux (above 30 m^3/m^2hr), produced a similar combustion temperature as in Run 8 (air flux of 20 to 8 m^3/m^2hr) approximately 250 C. The combustion front velocity in Run-7 was about two times faster than Run-8 (31 versus 16.3 cm/hr).

This increase of temperature by increasing the air flux agrees with **Yannimaras (1995)** , who carried out experiments on light oils (API 34) in situ combustion at high pressure condition. They reported that, sufficient fuel must be available to the combustion front in order to generate enough energy to heat the matrix to high temperature.

Table 5 - 5 The effect of air flux.

		Run 3	*Run 4*
Crude oil		Clair	Clair
Sand type		W50(Coarse)	W50(Coarse)
Clay content (wt %)		10	10
Injected air flux (m^3/m^2 hr)		60 - 75	20
Combustion temp (C)	***maximum***	804	500
	average	700	460
Stable combustion period (min)		72	115
Combustion front velocity (cm/hr) avg.		14.4	11.2
CO2 in production gas (%)		13	15
CO in production gas (%)		4	4
CO/(CO+CO2) ratio		0.28	0.27
H/C ratio of fuel burned		0.35	0.82
Air to fuel ratio (Sm^3/kg)		9	9.5
O2 Utilisation (%)		98	96
Combustion volumetric sweep (%)		19	18
Oil recovery (% OOIP)		39.8	35.6
Fuel burned (% OOIP)		3.1	1.5

5.3.4 Effect of Pressure

The combustion front velocity for medium Clair oil Runs 3, 5 and 6, (Table 5.4) appeared to be increased as the operating pressure was increased from 50 bar to 100 bar. This could be explained as, higher pressure leads to higher oxygen partial pressure, which in turn results in faster reaction rate according to equation 2 .3. Fuel laydown was also slightly increased using higher pressures.

5.3.5 Type of Crude Oil

The combustion temperature for light Australian oil (38.78 API), in Runs-7 and 8 was around 255C (average). This is much lower than for the medium Clair oil (19.8 API), where the combustion temperature ranged between 460C and 700C. Obviously, this is because of there was less fuel available for the light oil.

(distillation residue for Clair oil is 33.4, while for light oil is only 11.9 **Izadpanah 1996)**

Lerner et al (1985), who studied the dominant processes of in situ combustion, concluded that, for light oils the peak temperatures are expected to decline rapidly as the onset of combustion progresses away from the injection well. Ignition could have happened downstream, if the region temperature is high enough and oil is not completely desaturated (Jump phenomenon)

The combustion peak temperatures of runs 7 and 8 were around 250 C. This shows very satisfactory agreement with **Tzanco et al (1990),** who carried out laboratory combustion tests on Countess B, light oil (28 API) at pressure of 97 bar. The authors reported six tests with average peak temperature of 254C to 283C. **Yannimaras (1995),** also reported a high pressure combustion tube test on light oil(34 API) which gave a combustion peak temperature of 282 °C.

5.3.6 Sand Type

The effect of different sand type on the in situ combustion of medium Clair oil can be seen by comparing Runs-5 and 6 (table 5-6). Using the fine sand (W50, surface area 1643 m^3/kg) with 10% clay content in Run-5, resulted in higher combustion temperature 600C compared to only 450C in Run-6, which used the same flux but coarser sand (W50, surface area 1613 m^3/kg). The higher surface area of fine sand provided more surface for fuel deposition. The lower permeability and high porosity of the fine sand (Table 5.1) may have contributed to a higher temperature due to there being a higher oil saturation in the combustion region.

Table (5 - 6), the effect of sand surface area.

	Run 5	***Run 6***
Crude oil	Clair-19.8 API	Clair-19.8 API
Sand type	W150(Fine)	W150 (Coarse)
Clay content (wt %)	10	10
Specific surface area (m^2/kg)	1643	1613
Permeability (md)	616	1004
Porosity (%)	43	36
Combustion temp. (C)	600	450
Stable combustion period (min)	93	247
Combustion front velocity (cm/hr)	15.3	20.2
CO2 in production gas (%)	10	15.2
CO in production gas (%)	3	5
CO/(CO+CO2) ratio	0.25	0.27
H/C ratio	2.25	0.38
Air to fuel ratio (Sm^3/kg)	11.75	8.85
O2 Utilisation (%)	84 - 96	77 - 91
Combustion volumetric sweep (%)	26	56
Oil recovery (% OOIP)	40	83
Fuel laydown gm/100gm	1.45	2.54

5.3.7 Adiabatic heat control

At high combustion temperature peaks (above 350C), only partial adiabatic heat control was possible, because the band heater power supply was limited to 50% of full power, and its response time is slower compared to the combustion front movement, these restricted the maximum temperature achievable to only 300C In Run-7 and 8 some modifications was carried out to improve the power supply.

This resulted in great improvement in the band heaters capability, and the resulting adiabatic temperature can be seen in Figures 5-31 to 5-36. The best performance occurred in Run-8 (Fig 5.36), 120 minutes from ignition, in which the axial temperature were exceeded 250 C, and the differential between the axial and wall temperature was controlled to less than 20 C. However, in Run-6 (Figs 5.31 and 5.32), the agreement between the axial and wall temperature is less good in the region of the combustion front. The limitation on the maximum wall temperature is clearly evident at above 350 C.

5 .4 COMBUSTION PERFORMANCE PARAMETERS

Complete combustion is described by the equation (Burger 1985)

$$CH_x + (1 - \frac{r}{2} + \frac{x}{4})\, O2 \longrightarrow (1-r)\, CO2 + r\, CO + \frac{x}{2}\, H_2O \qquad (5.1)$$

Where r = CO / (CO+CO2)

x = hydrogen / carbon ratio of the fuel (H/C)

The value of CO and CO_2 obtained depend very much on the nature of the oxidation reactions. Incomplete combustion usually results in increased values of CO , while high temperature reaction produces only CO_2 and water. Hence the value of the CO / (CO_2+CO) ratio will be zero in the later case. It will increase if incomplete combustion occurs.

The H / C ratio level is a very important indicator as to which kind of fuel is being burned. Hence the H / C ratio can vary according to the type of oil(heavy or light) and the occurrence of LTO ,where H/C reaches high values. A value of H/C greater than 2.5 is assumed to be indicative of LTO occurring. For high temperature oxidation (HTO) H/C values fall in the range of 0.3 to 1.5.

The atomic hydrogen / carbon ratio is calculated using the equation (Burger 1985):

$$H/C = X = \frac{1.06 - 3.06Yco - 5.06(Yco2 + Yo2)}{Yco2 + Yco} \qquad (5.2)$$

Where Y = mole fraction of produced gases.

Fuel laydown

The amount of fuel burned as percentage of the original oil in place (OOIP) is calculated from the equation:-

$$\text{fuel burnt as \% of OOIP} = 100\left(\frac{O2..consumed}{air.fuel.requirement * 0.21}\right) / OOIP \qquad (5.3)$$

The fuel laydown is calculated by dividing the mass of fuel burned by the mass or volume of sand matrix swept by the combustion.

Air to fuel requirement

The standard volume of gas required to burn a mass m_c of fuel is found from the equation (Burger 1985):

$$Vg/m_c = \frac{b}{y_{o2}} \frac{2 - r + \frac{x}{2}}{12 + x} \qquad (5.4)$$

Where: b = coefficient (11.82 sm^3/kg)

r = CO / (CO +CO_2).

b/yo_2 = 56.3 sm_3/kg when air is the injection gas

10 to 12 sm^3 of air are normally required to burn 1 kg of fuel in high temperature combustion reaction.

5.5 Produced gas composition:-

Figures 5-7 to 5-12 and Table 5.7 give the composition of the produced gases. Runs 3 to 6 (Clair oil) are characterised by high values of CO_2 ranging between 10% and 15.2%, while CO is between 3% and 5%. These runs are accompanied by high oxygen utilisation, over 91% in the stable combustion zone, and average combustion temperatures of 400C to 700C.

In Run-3,(Figure 5-13), all of the injected oxygen was essentially consumed from the start of air injection. The CO_2 increased sharply (Fig 5.7) from ignition and reached 16% after 0.8 hour, then decreased to 8%., as the combustion temperature reduced from 700C to 500C . During this period, there was a increase in CO, but no change in the oxygen utilisation. The increase in CO is evidence of LTO reaction, but after 2.75 hrs the combustion temperature increased again signifying apparent 'jump' phenomena referred to previously in section 5.3.2

In Runs 7 and 8 (Australian light oil), CO_2 values averaged 5.5%, whilst the CO values ranged between 1.18% and 1.4% (Table 5-4). The lack of fuel in case of the light oil was the main reason for not achieving a high combustion temperature, and in consequence, the low values of CO_2.

In the Runs 3 to 6, analysis of the dry combustion gases showed no evidence of the presence of light hydrocarbons or hydrogen being produced.

5.6 Apparent H/C, CO/(CO+CO2), Fuel Consumption and Air to Fuel requirements

The apparent H/C ratio and CO/CO+CO2 ratio were calculated from the analysis of the produced gases. The H/C ratio was calculated on the assumption that all of oxygen which did not appear in the exit gases had reacted to form water.

This is not be strictly true, because of the possibility of LTO reactions occurring. Any LTO reaction effect would be evidenced by a low level of CO_2 in the exit gases, because more oxygen will react with hydrogen than would react with carbon to form carbon oxides. It is noticed that, the apparent H/C ratio is always high at the start of any combustion test. This is probably due to the dispersion effect arising from the different gas components. High H/C ratios also reflect that low temperature oxidation reactions precede the onset of high temperature reactions. However these initial values should not be included in final calculation as they do not represent the actual performance of the combustion process. The range of H/C values are more important than the actual values as it is impossible to assign an H/C ratio to a specific location along the tube length. This because the H/C ratio reflects the oxidation reaction over the total length of the elevated temperature region.

Figures (5-19) to (5-24) show the plots of H/C, $CO/CO+CO_2$ and Vg (volume of gas required), those values are found also for all experiments in Table 5.7

Table (5 -7) Produced Gas Composition and Fuel Laydown.

RUN	*3*	*4*	*5*	*6*	*7*	*8*
Oil Gravity- (API°)	19.8	19.8	19.8	19.8	38.78	38.78
Combustion Temp (C)	700	460	600	450	255	250
CO_2 %	13	15	10	15.2	6.4 -11.3	6.5 - 8.3
CO %	4	4	3	5	1.2 - 2.3	1.4
O_2. Utilisation %	98	96	84 - 96	77 - 91	29 - 90	42 - 94
$CO/CO+CO_2$	0.25	0.27	0.25	0.27	0.21	0.18
H / C	**	0.82	2.25	0.38	4 - 7.2	6.5
Air to fuel requirement sm^3/kg	9	9.5	11.75	8.85	15.57	15
fuel laydown gm/100 gm	2.04	1.05	1.45	2.54	0.53	0.37

Fuel laydown = grams of fuel (coke) to 100 grams of sand mixture.

**** = It was difficult, to calculate these values precisely, due to instability of air injection .**

In Run-3, The values of $CO/(CO_2+CO)$ was fairly steady, averaging 0.25 over the experiment. The high value of CO_2 indicating high combustion efficiency, where most of the oxygen was consumed in the high temperature zone producing substantial amounts of CO_2. Calculated air fuel ratio required was 8.57 sm^3/kg. In Run-4, H/C ratio was 0.82 while $CO/(CO+CO_2)$ kept as same as for run-3 and the air to fuel required increased by 1.0 sm^3/kg . The flux was the main factor to blame over the changes in results between run-3 and run-4. -See Table (5-5), (*effect of air flux).*

In Run-5, can be seen the effect of using fine sand with 10% clay, which reflected in high surface area and in turn more fuel was available. H/C ratio was 2.252 and air to fuel ratio increased over Run3,4 reaching 11.75 sm^3/kg . Fuel lay down also increased over run 4 with 26% up to 1.45gm/100 gm, while $CO/(CO+CO_2)$ ratio kept steady at average of 0.25.

In Run-6, it can be seen clearly, that there was a similarity of results with run-3, in terms of $CO/(CO_{2+}CO)$, and air to fuel requirement. The slightly change which could be referred to the effect of flux, was the increase of fuel lay down in run-6 (2.54 gm/100gm), which increases by 25% over run-3. The pressure could also contribute in fuel laydown as run-6 was done at pressure of 100 bar

In Run-7 and Run-8 (Australian light oil), the trend of results as it can be seen in Table 5.8 shows the difference in the process nature between light oil and medium oil (the first four runs).

Table (5.8), Comparison of the combustion parameters for light and medium crude oil experiments.

	Medium oil(Clair - 19.8 API)		*light oil (Australian- 38.78API)*	
	High flux ***Run6***	*Low flux* ***Run4***	*High flux* ***Run7***	*Low flux* ***Run8***
Injected air flux (m^3/m^2hr)	60	20	30 - 100	20 - 8
Run pressure (bar)	100	50	70	70
Combustion temp. (C)	450	460	255	250
combustion period (minutes)	247	115	155	330
front velocity (cm/hr) av	20.2	11.2	31	10.2
CO2 (%) av	15.2	15	6.5	6.5
CO (%) av	5	4	1.2	1.4

The light oil runs failed to achieve a high combustion temperature. The process therefore, could be classified mainly as LTO reaction. Run-7 and 8 had very similar results in terms of H/C (8 and 6.52), $CO/(CO+CO_2)$ (0.21 and 0.18), air to fuel requirement (15.57 and 15sm3/kg) and fuel laydown (0.53 and 0.37gm/100gm). However when comparing the results against those obtained
with Clair oil, as it can be seen in table 5.8 , that Run-7 and 8 produced less CO and CO_2, because less carbon was burned. The medium oil runs average values
of CO and CO_2 at 3% and 12% respectively, while light oil runs had average CO and CO_2 of 1.2 and 6.4 respectively.

Runs 7 and 8 of light oil are mostly described as LTO to MTO reactions as both runs failed to reach a high temperature oxidation mode, which is defined by **Dabbous** and **Fulton** (1974) to be in the region of 300 to 315 °C. These authors reported that below this temperature, most of the oxygen consumed is utilised in hydrogen and hydrocarbon oxidation reactions rather than in carbon oxidation to carbon oxides.

Yanimaras(1994) used Accelerating Rate Calorimetry (ARC) to study light oil performance. In general he found, for light oils (12 candidate oils), 20% are good candidates for propagating full ISC. This suggests that possibly 80% of light oils will sustain only low temperature oxidation(LTO).

The levels of the apparent H/C ratios and temperature reached for the light Australian oils suggests that, the combustion kinetics are different for these oils compared with these for the medium oil. The results obtained from Run 7and 8 show satisfactory agreement with other researches conducted on light oils.

Hardly et al (1972) described the May-Libby ,Delhi project that involved a 40 API gravity light oil. They reported an apparent H/C of 3.1 for this project. This H/C ratio value is significantly higher than the actual atomic H/C of the native oil, suggesting that either significant LTO reaction was present, or the fuel from the process was not coke. **Boyle et al** (1984), who reported on the Countess B in-situ combustion project, found that the apparent atomic H/C ratio was 3.6 in presence of LTO. **Moore et al**(1990) who carried out 15 in situ combustion tests on a 28 API oil, reported that there were two stages of oxidation reactions. The first occurred at a temperature in the range of 260 to 270 C. This was associated with an average apparent H/C ratios between 6.0

and 2.8 and air to fuel requirement between 11.5 and 15.4 sm3/kg. The second stage in the combustion mode happened at a temperature in the region of 310 to 350 C, with much lower values of H/C ratios.

Geaves et al(1995) who carried out a 3D tests on light oil in situ combustion under water flooded conditions, reported a higher of H/C of 4.0 to 4.2 in some tests, stating significant LTO reaction probably occurred in these tests.

The H/C ratios for light oil at high pressure and high temperature (if HTO is achieved) are much lower than those values occurring under LTO conditions. **Fassihi and Yannimaras(1994)** reported that H/C ratio of the fuel of light oil at high pressure and high temperature combustion in air injected projects was around 2. **Wilson(1997)** reported that some 3D experiments on light oil failed to achieve HTO. He considered that the main reactions which occurred were LTO, giving very high values of the H/C ratio between 11.6 to 20 and air to fuel requirements of 17 to 21 sm^3/kg.

The dominant factor governing the propagation of a stable temperature front in a light oil reservoirs is the amount of fuel available either for combustion or LTO. The fuel in Runs 7 and 8 was mainly the heavy fraction of the light oil, or some oxygenated hydrocarbons, which leads to high H/C ratio values between 6.2 to 8. The fuel laydown was around 0.35 to 0.55 gm/100gm mixture, which is about four to five times less than medium Clair oil. While the fuel consumption in Run 6 (Clair) was 11% OOIP, it was only 4 and 2.3% in Run7 and 8 respectively.

Very similar results were reported by **Greaves et al (1995)** , who reported a low fuel consumption values of 3.5 to 4.5% OOIP for light oil. This was about one third the level observed for medium and heavy oil in situ combustion.

The highest oxygen utilisation occurred in Runs 3 and 4(Clair oil), where the overall oxygen utilisation reached 97%. These two runs were characterised by high combustion efficiency, which resulted in almost full oxygen consumption within the high combustion temperature zone, hence producing substantial amounts of CO2. This result is in good agreement with values obtained by **Guvenir (1980)** and **AL-Shalabe (1985)** for the same type of sand and clay content(10%).

A significantly lower oxygen utilisation was observed in Run-7 and 8(light oil), but this mainly corresponded to the periods of very high injection flux. However, as the air flux was lowered to a value more in line with the limited amount of fuel available, the oxygen utilisation improved, reaching a maximum of 94%. (see Figs 5.17 and 5.18). Therefore the air flux must be low enough, so that the residence time of the oxygen in the reaction zone is long enough for all the oxygen to be consumed.

5.7 Oil and water production

In the full automated high pressure combustion tube, the oil and water production from the low pressure separator on volume base is discharged to the rotating sampler, where individual samples are collected in a 120cc jars.

It was noticed in all of the runs that, no oil nor water production occurred during the pressurisation and heating stage. None, or very little liquid production occurred in the period from the start of air injection and the moment of ignition. In the experiments on medium Claire oil (Run-3 to 6), production was delayed some time after ignition, but in the light oil experiments(Run-7 and 8) production started just before ignition in the case of Run-7, or at ignition in the case of Run-8. This is because the light oil is more mobile and faster responds to heat evolved in the process.

The oil production in all runs started first at a high rate at the beginning of each experiment. It then gradually reduced as combustion or temperature front moved further down the tube. Water production in all runs was delayed sometimes after the start of oil production, starting when the combustion became more stable and the effect of steam and flue gases displacement became more effective. The water production rates started at a relatively low rates, and gradually increased toward the end of the runs when the production was mostly water. Table 5.9, illustrates the oil and water production results.

Table (5 - 9) - Oil and Water production

Run	*3*	*4*	*5*	*6*	*7*	*8*
Initial oil (API)	19.8	19.8	19.8	19.8	38.78	38.78
OOIP (cc)	2120	2120	2120	2120	1450	1600
OWIP (cc)	1240	1240	1240	1240	1770	1770
Oil produced (cc)	845	755	848	1760	627	959
Water produced (cc)	175	75	96	719	765	747
Oil recovery (%OOIP)	39.8	35.6	40	83	43	64
Water recovery (%OOIP)	14.3	6	7.7	58	41	42
Oil produced (API)	19.8	19.8	19.8	21.2	39.1	44.1
Fuel burn (% IOIP)	3.1	1.56	3.2	9.5	4	2.3

For medium Clair oil, the oil production in Runs-3,4 and 5 was 35.6 to 40%OOIP and the water production was 6 to 14%, but in run-6 with the same oil the corresponding oil and water production was 83% and 58. The difference in the results between the first three runs and Run-6 is mainly because the first runs were terminated early (for technical reasons). The effect of air flux on production performance can be seen clearly by comparing Run-3 and Run-4. Although Run-3 lasted for only about half that of Run-4, they both had very similar oil recoveries (39.8% and 40%OOIP, respectively). This was because Run-3 was performed at much higher air injection flux (60 to 75 m3/m2hr), compared with Run-4 (20 m3/m2hr). Production history profiles are presented in Figures 5 .37 to 5 .39. Production profile of Run-6, Fig (6-37) represents the total liquid production (oil + water) and it was calculated according to the discharging rate from the high pressure separator. The production was collected as cumulative, thus it was unable to perform oil and water production rate profiles individually

The production recoveries of the light oil experiments (Run-7,8), were 43% and 64% for oil and around 42% for water. The production rates were very affected by the injected air flux and the combustion front advancement, which accelerated the production and significantly reduced the production time

Conclusions

Satisfactory development and commissioning of the combustion tube facility was achieved.

Medium Heavy Clair oil Experiments

1. Four in situ combustion experiments were carried out using medium heavy Clair oil (19.8 API) at pressures between 50 and 100 bar and with air injection fluxes between 20 to 85 sm^3/m^2hr . All of the experiments achieved high temperature combustion with an average combustion temperature between 450 C and 650 C.

2. Very high Oxygen utilisation in a stable combustion zone were achieved, ranging between 91 and 97%. Substantial levels of CO_2 were obtained (10 to 15.2%) and with CO levels of 3 to 5%. The considerable amounts of steam generated, in addition to the flue gases resulted in a fast and efficient sweep of the sandpack.

3. In all of the runs, a high level of gas communication was present throughout the bed. The good gas connectivity following gas injection, caused the liquid production to be delayed, but no desaturation of the sandpack occurred. Oil production started as the ignition was initiated or shortly afterwards, indicating that the displacement was as result of the combustion factors rather than the injected gas effect. The production was accelerated by higher air injection fluxes and higher combustion temperatures (more steam generated). The oil recovery was between 40 and 83%, but it was noticed that only 1/3 to 2/3 of the tube length, was needed to be burnt to obtain these ultimate oil recoveries.

4. For the medium oil, a higher air injection flux, up to 75 sm^3/m^2hr resulted in higher combustion temperatures (600 to 800 C) and faster combustion front movement. The oxygen utilisation in the stable combustion zone also stayed very high (around 96%), when the air injection flux was increased from 20 Sm^3/m^2hr to 75 sm^3/m^2hr. This indicates that sufficient fuel was available to consume all the injected oxygen when a high air injection flux was used.

5. The H/C ratio of the fuel for Clair oil, was in the range of 0.36 to 2.25, indicating that most of the fuel for combustion was coke, rather than any light or heavy fractions of oil. The air to fuel requirement was around 9 sm^3/kg, but increased to 11.75 sm^3/kg in Run-5, which used fine sand.

6. A higher air injection flux led to an increase in the fuel laydown. Increasing the flux from 20 m^3/m^2hr (Run-4) to 75 m^3/m^2hr (Run-3) increased the fuel laydown by about 50% due to higher levels of thermal cracking at the high temperature achieved. Fuel laydown was also increased slightly, when the operating pressure was increased from 50 to 100 bar.

Light Australian oil Experiments

1. The experiments failed to achieve a high temperature combustion mode due to lack of fuel. However the process nevertheless sustained a very stable, 'high' temperature front propagation at around 250^{0}C. Because of the lower temperature, it is considered that the reactions occurring were mainly LTO. The CO2 and CO levels in the production gas were quite low at 6.5% and CO 1.2% respectively.

2. Very little, or no coke was formed during these tests. The fuel was mostly oxygenated hydrocarbon products together with the heavy oil fraction. This is confirmed by relatively high H/C ratios (6.5 to 8) and the high air to fuel requirement (around 15 sm^3/kg).

3. Increasing the air flux did not increase the combustion temperature, due primarily to the limited amount of fuel available, but it did accelerate the combustion front velocity and liquid production. However, if the light oil process essentially operates in a LTO mode, because the oil is not a good ISC candidate, then a low gas injection rate is preferable to stabilise the process performance.

4 . The high oil recoveries up to 65% with the light Australian oil, indicate that , there is great potential for using LTO, as a recovery technique for light oils which are not good candidates for high temperature ISC..

Recommendations for Future work

1. Further experiments need to be done on light oils. A wider range of crude oils, oil saturations, air fluxes, oxygen enrichment and operating pressures up to 200 bar should be investigated in order to evaluate the ISC/LTO processes of light oil. A full parameteric study could determine when, and whether, a LTO or ISC process, is the most suitable way to recover light oil, and under what conditions.

2. The experiments with light oil have proved that, much lower air requirement are needed compared with medium oil. However, the air requirement could be reduced further by using wet in-situ combustion.

3. Further work should be done to include the use of reservoir sands and consolidated media for further understanding of the effects of sand surface area, porosity and permeability on the process of in - situ combustion at high pressure conditions.

4. A 3D cell capable of high pressure conditions should, if possible be developed and experiments should be carried out on both In - Situ Combustion and LTO process in order to achieve more accurate data on sweep efficiency and combustion front velocity. However, this may be prohibitively expensive

5. An accelerated rate calorimetry (ARC) system is needed to determine the reaction kinetics parameters for a wide variety of crude oils, so that specific and precise data on the kinetics and combustion parameters are available for successful simulation modelling .

6. A technique is needed to determine the fluid relative permeability inside the tube . Specific data is necessary for each type of sand used, and also the fluid saturation along the tube for successful simulation modelling.

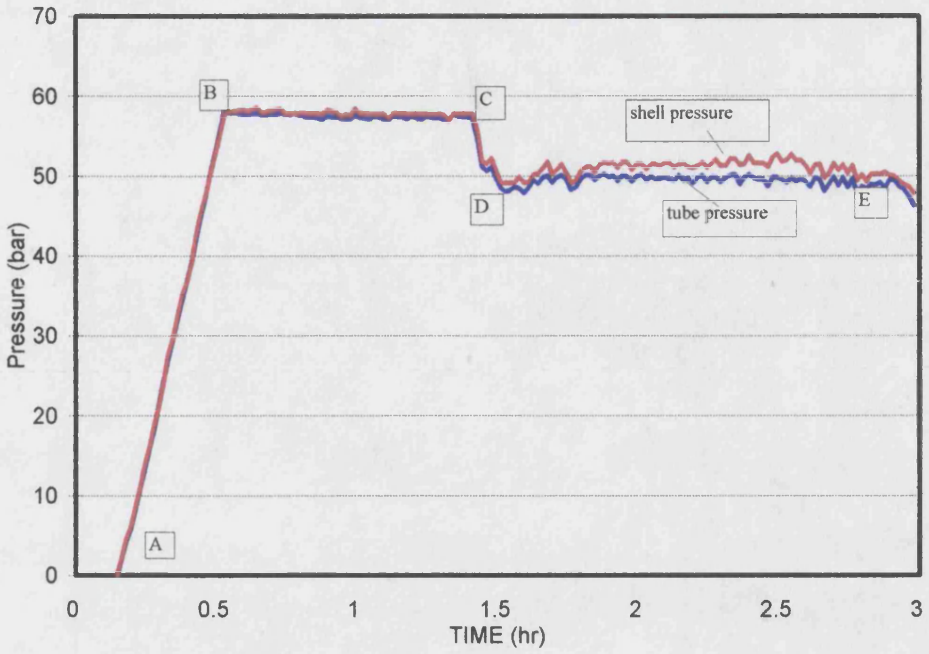


Fig 5.1 Pressure profile Combustion Tube Experiment (Run 3 - Clair oil)

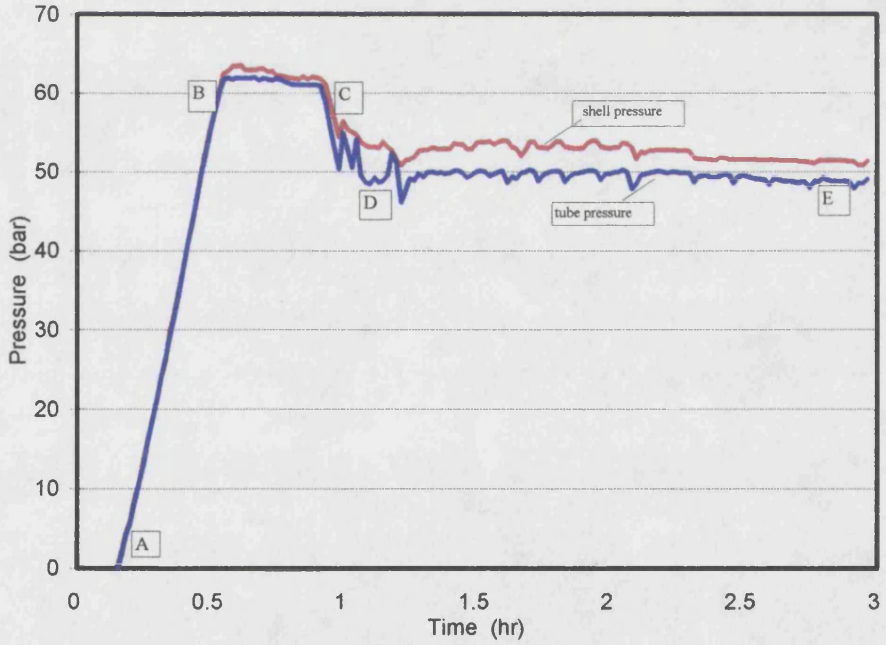


Fig 5.2 Pressure profile Combustion Tube Experiment (Run 4 - Clair oil)

A - B Pressurisation , B - C Heating up of sandpack to reservoir temperature
C - D Pressure drop to initiate air injection, D - E Operating pressure

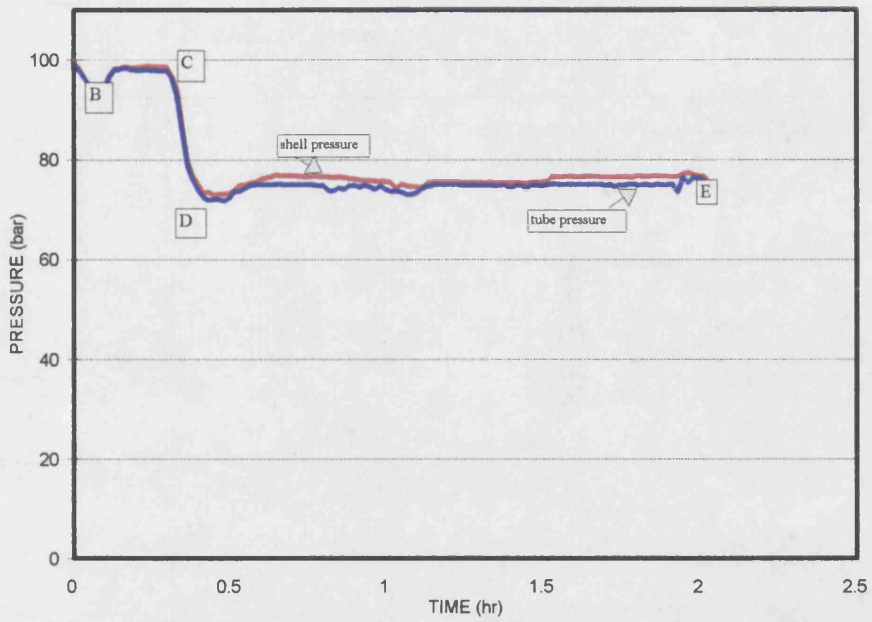


Fig 5.3 Pressure profile Combustion Tube Experiment (Run 5 - Clair oil)

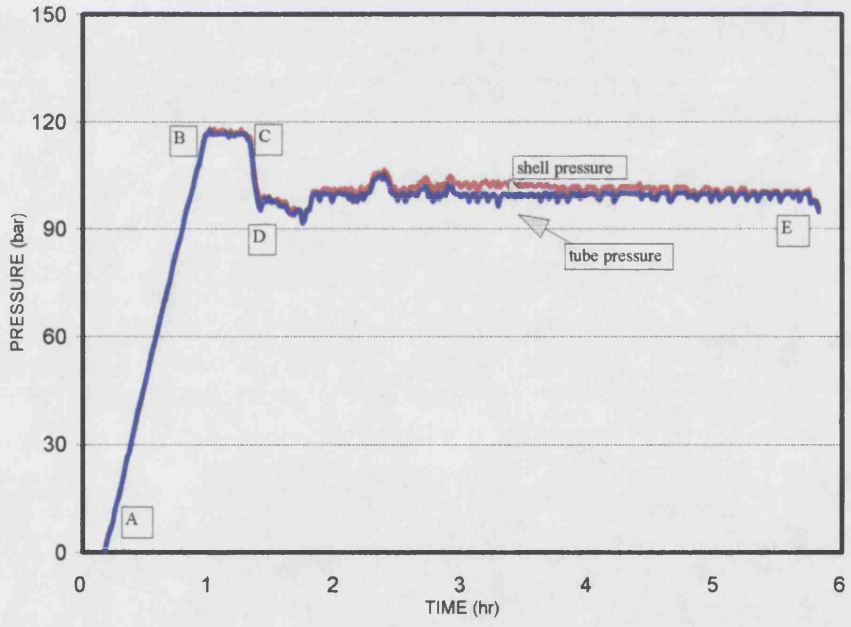


Fig 5.4 Pressure profile Combustion Tube Experiment (Run 6 - Clair oil)

A - B Pressurisation, B - C Heating up of sandpack to reservoir temperature
C - D Pressure drop to initiate air injection, D - E Operating pressure

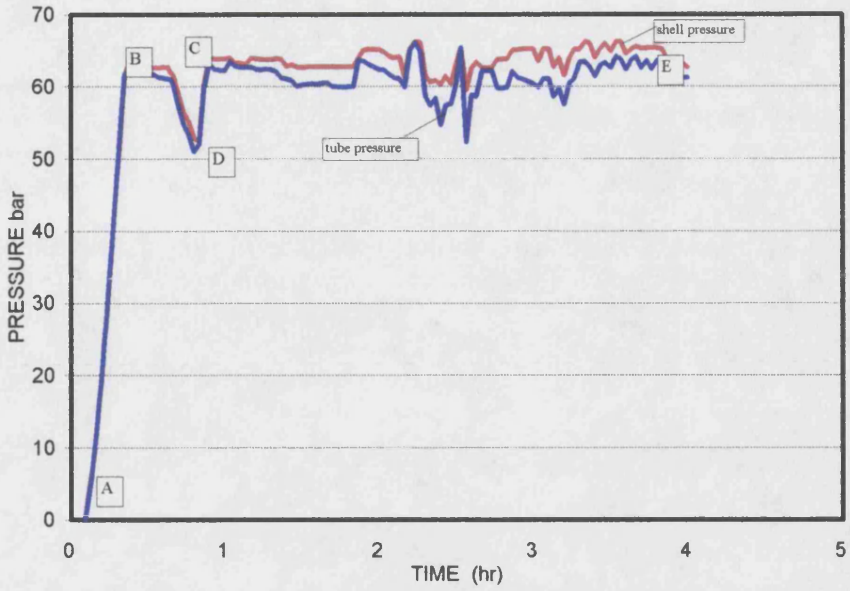


Fig 5.5 Pressure profile Combustion Tube Experiment (Run 7 - light oil)

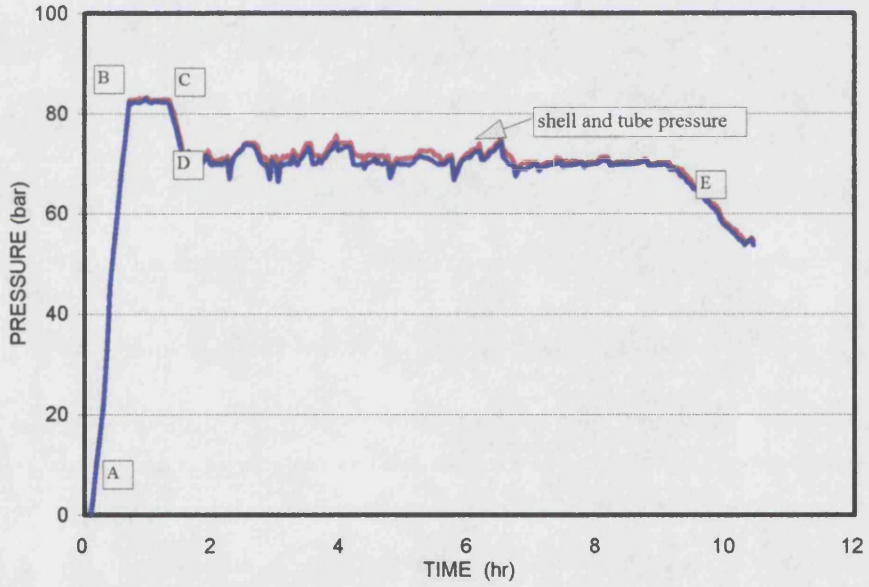


Fig 5.6 Pressure profile Combustion Tube Experiment (Run 8 - light oil)

A - B Pressurisation , B - C Heating up of sandpack to reservoir temperature
C - D Pressure drop to initiate air injection, D - E Operating pressure

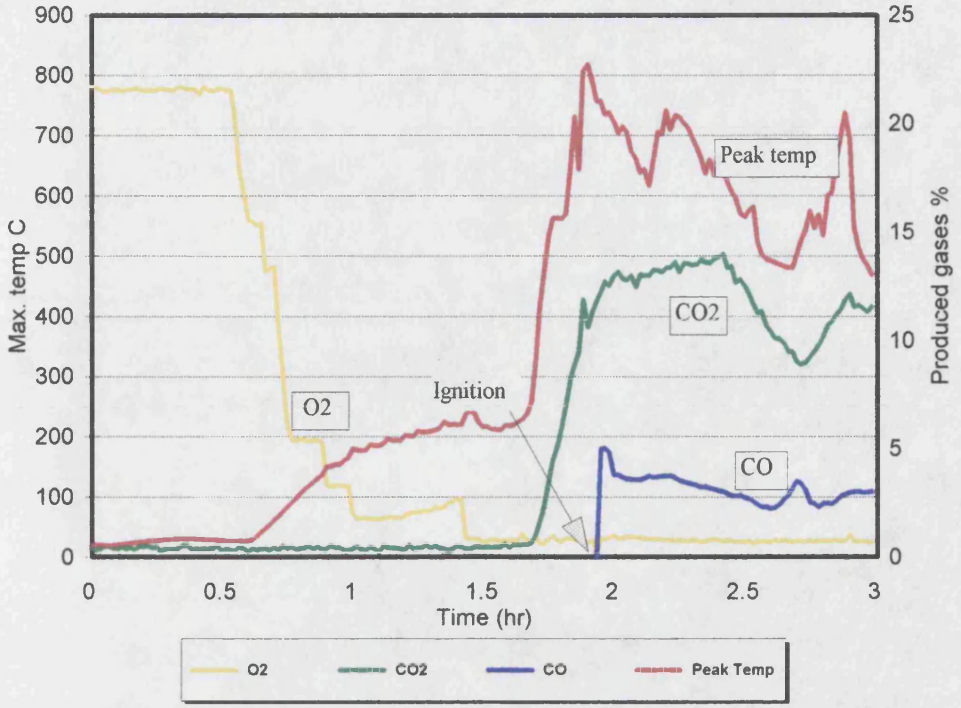


Fig 5.7 Combustion Peak Temperature and Produced Gas Composition (Run 3- Clair oil)

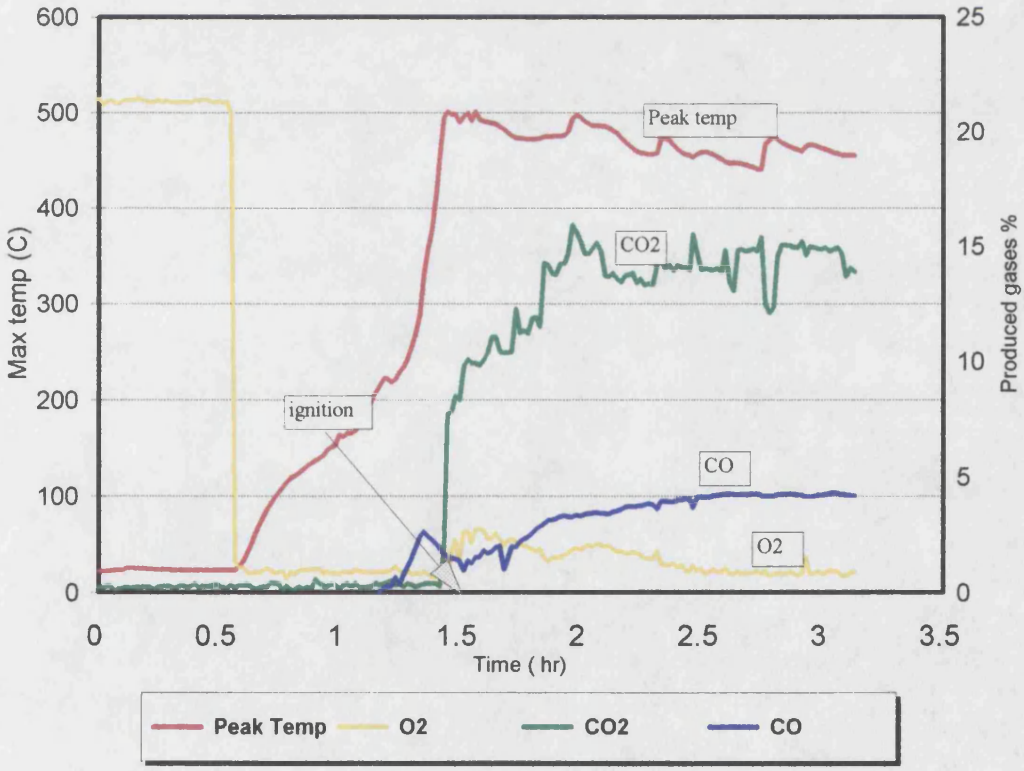


Fig 5.8 Combustion Peak Temperature and Produced Gas Composition (Run 4-Clair oil)

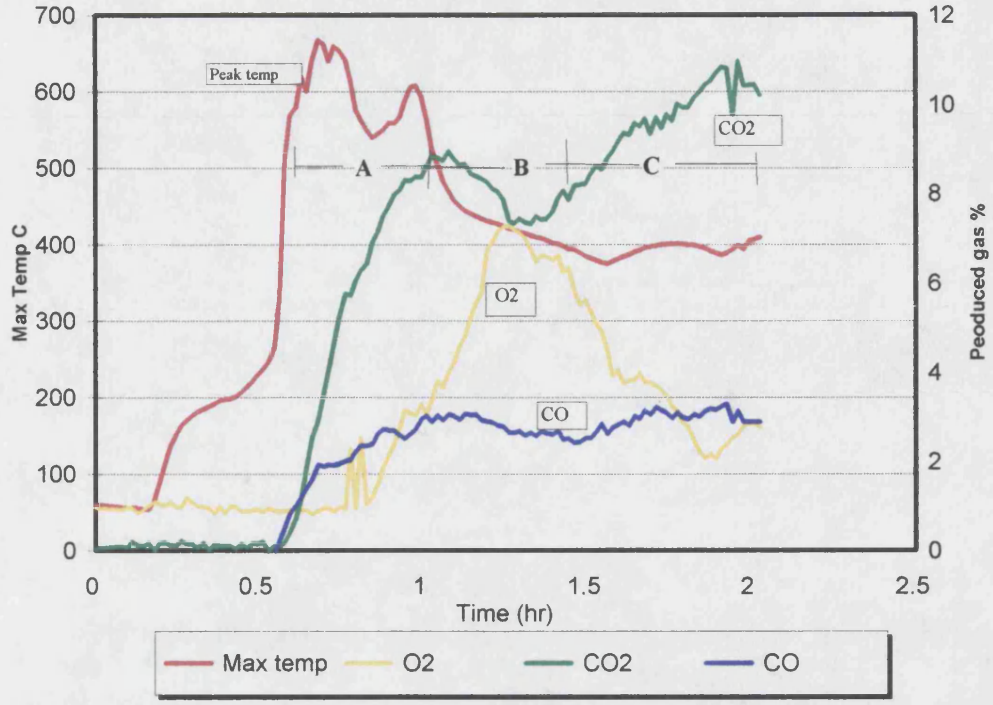


Fig 5.9 Combustion Peak Temperature and Produced Gas Composition (Run 5,Clair oil)

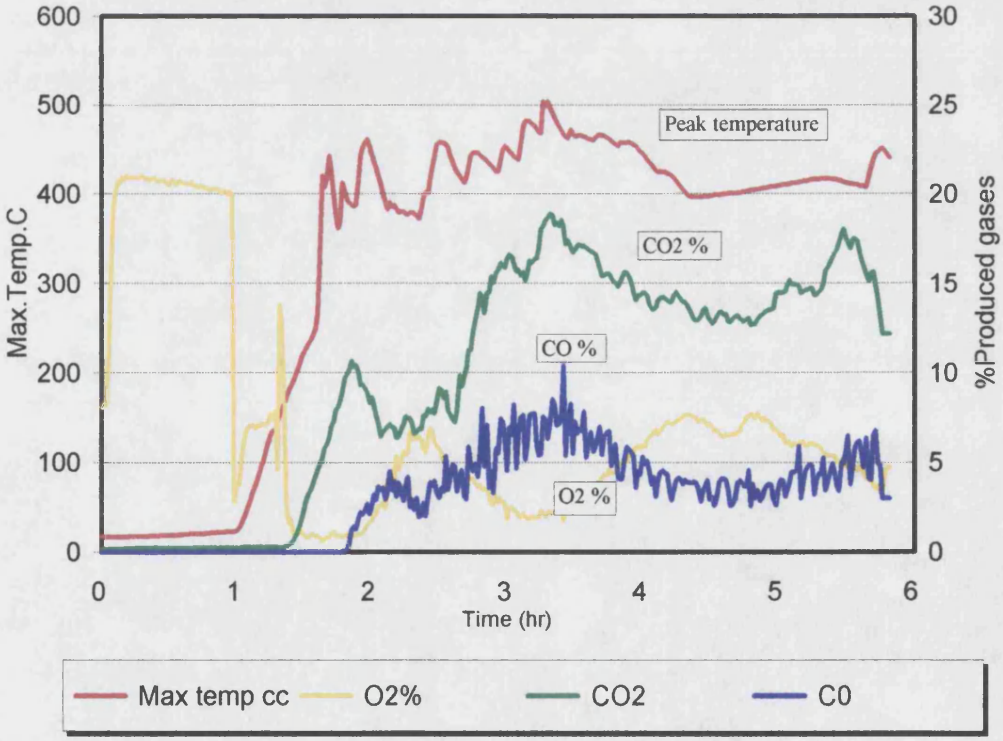


Fig 5.10 Combustion Peak Temperature and Produced Gas Composition (Run 6,Clair oil)

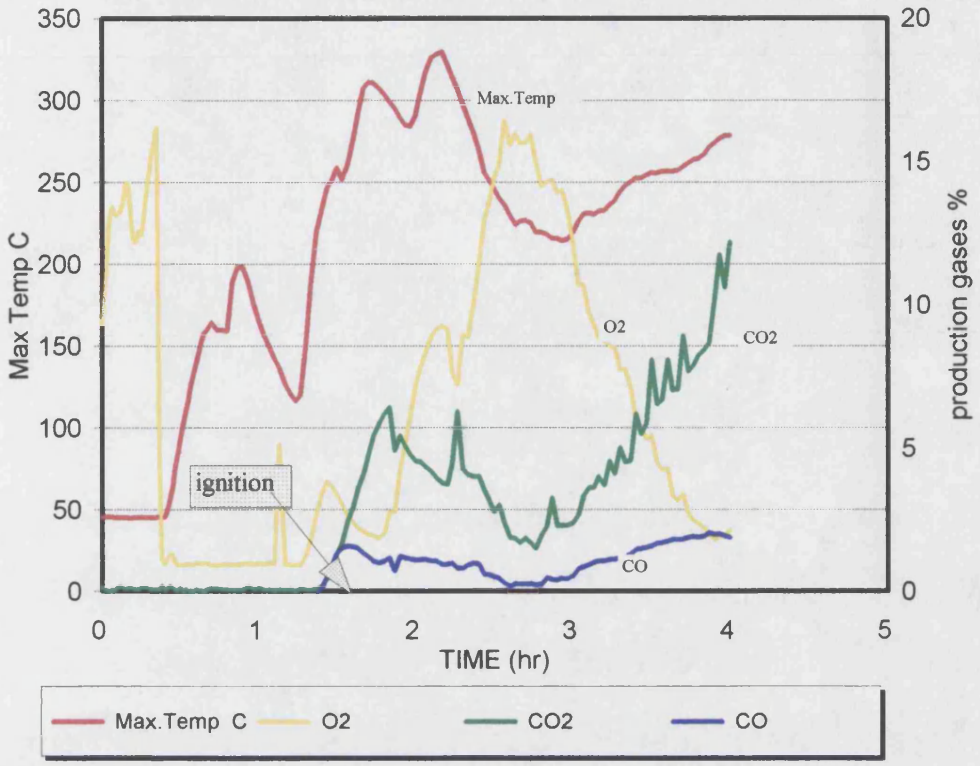


Fig 5.11 Combustion Peak Temperature and produced Gas Combusition(Run 7, light oil)

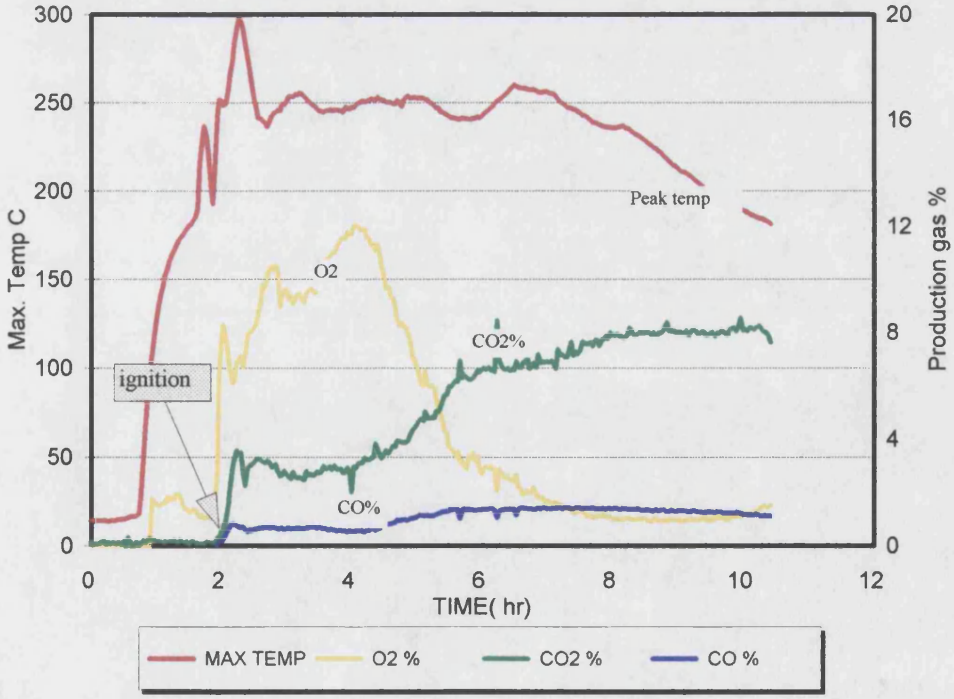


Fig 5.12 Combustion Peak Temperature and produced Gas Combusition(Run 8, light oil)

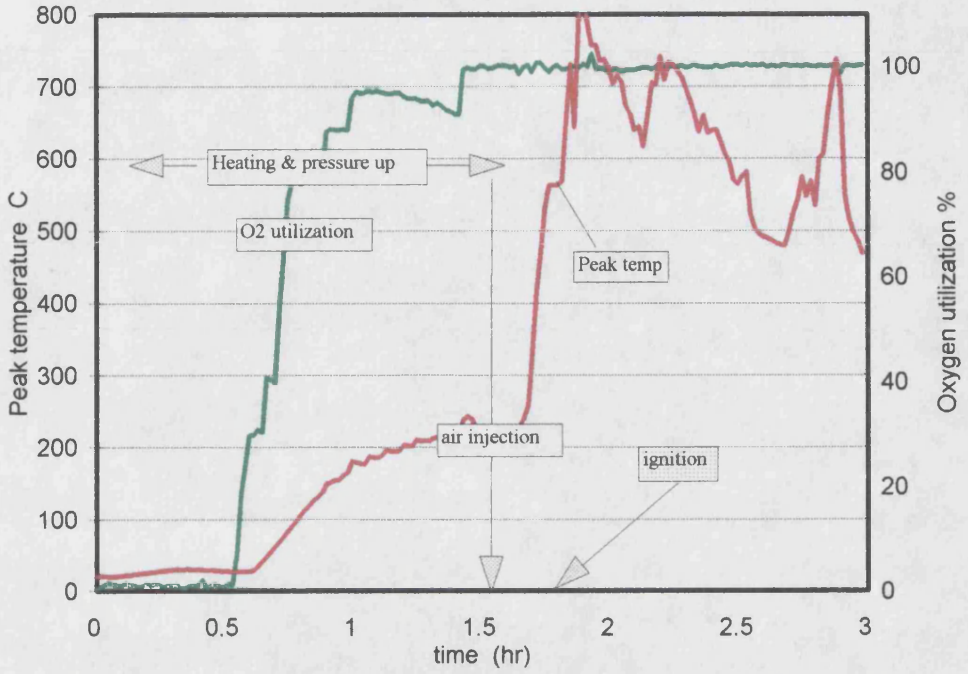


Fig 5.13 Oxygen Utilisation and Peak Temperature (Run 3 - Clair oil)

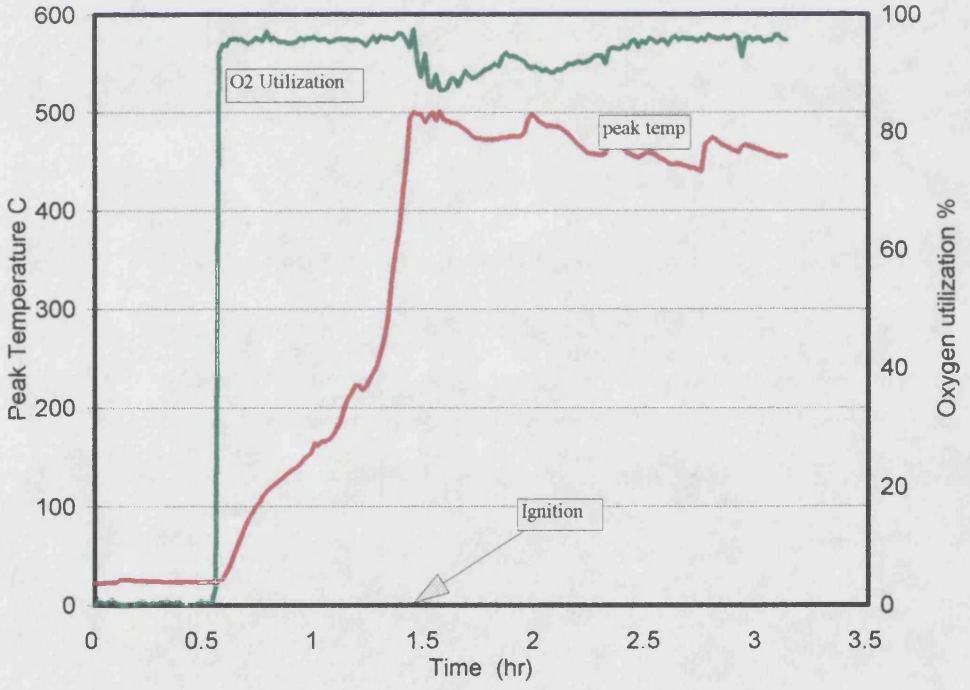


Fig 5.14 Oxygen Utilisation and Peak Temperature (Run 4 - Clair oil)

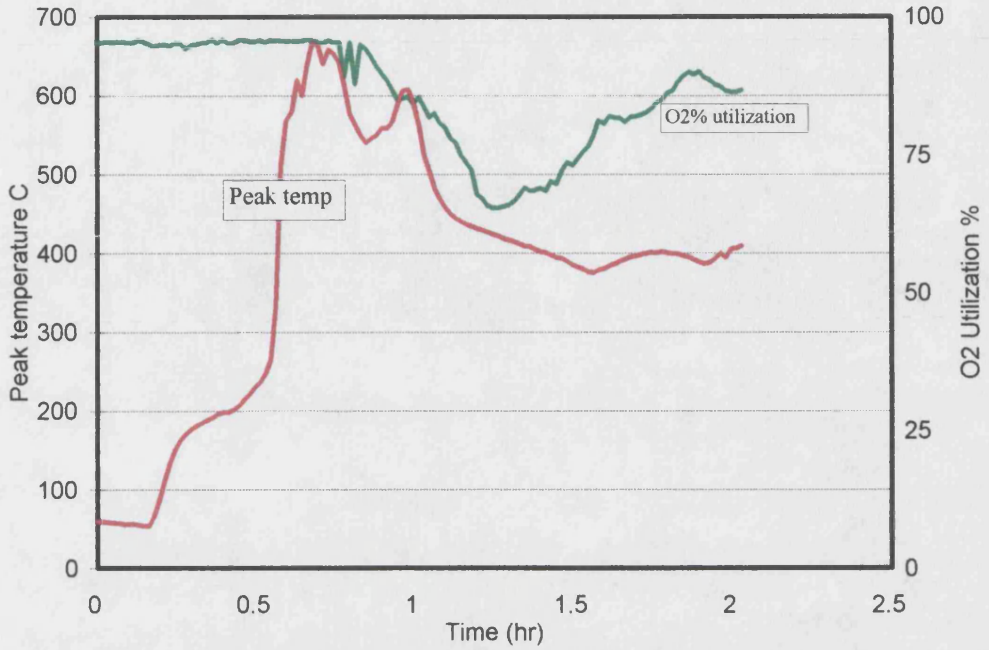


Fig 5.15 Oxygen Utilisation and Peak Temperature (Run 5 - Clair oil)

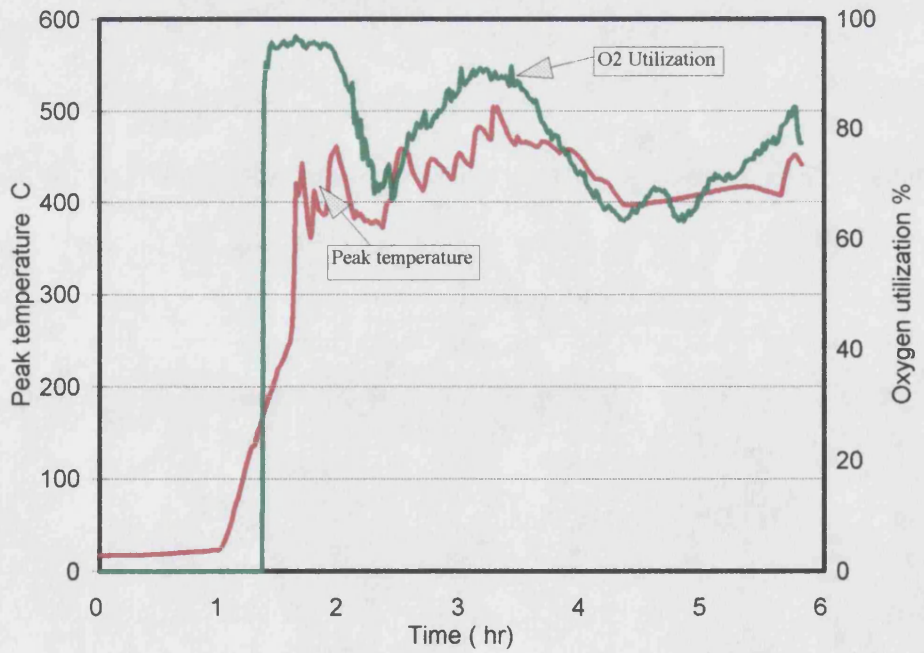


Fig 5.16 Oxygen Utilisation and Peak Temperature (Run 6 - Clair oil)

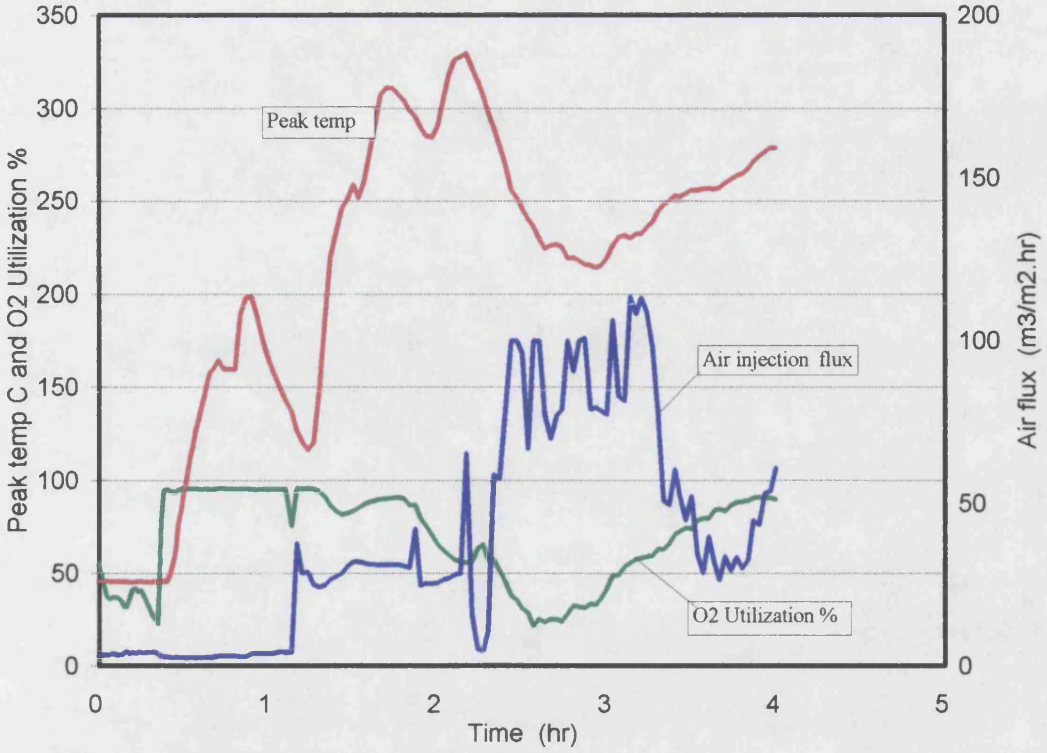


Fig 5.17 Oxygen Utilisation, Air flux and Peak Temperature (Run 7 - light oil)

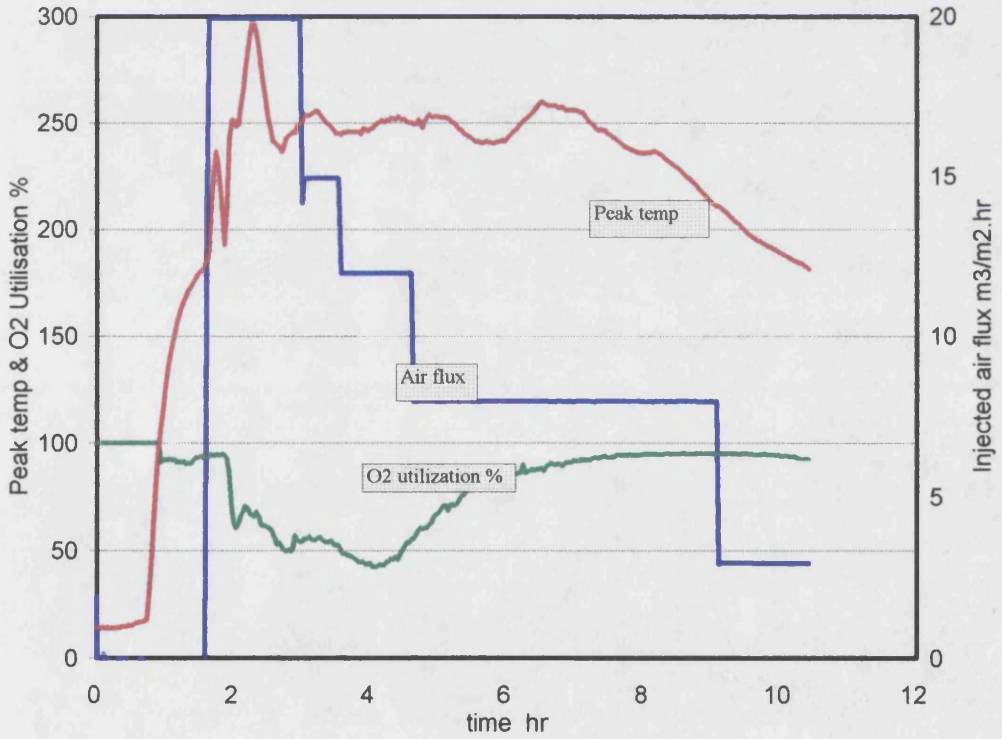


Fig 5.18 Oxygen Utilisation , Air flux and Peak Temperature (Run 8 - light oil)

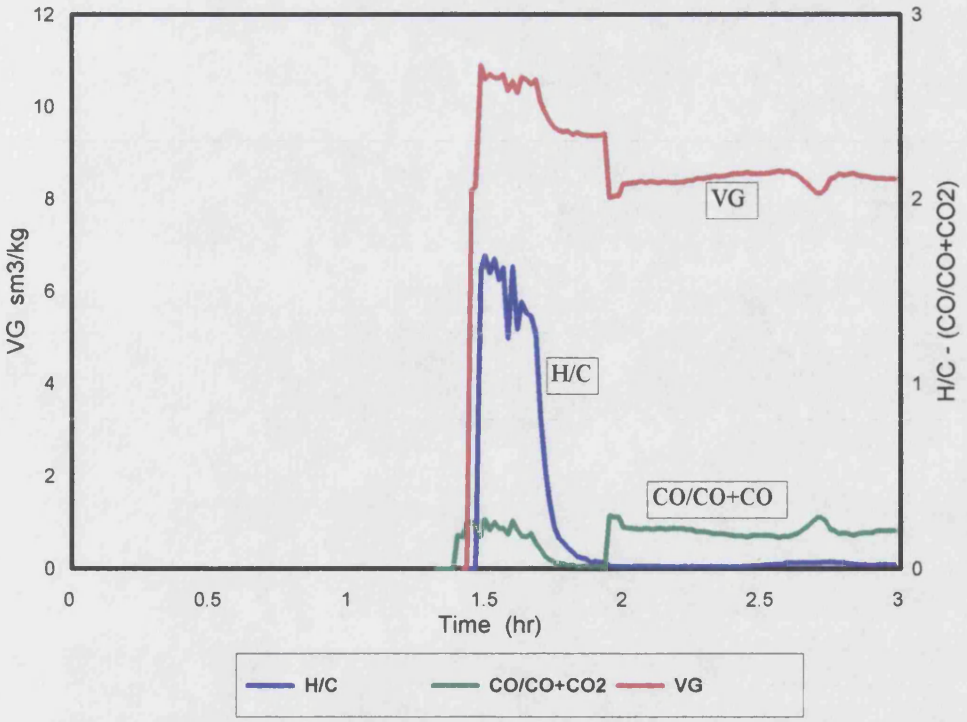


Fig 5.19 CO/CO+CO2, H/C and VG (volume of air required) - Run 3 - Clair oil.

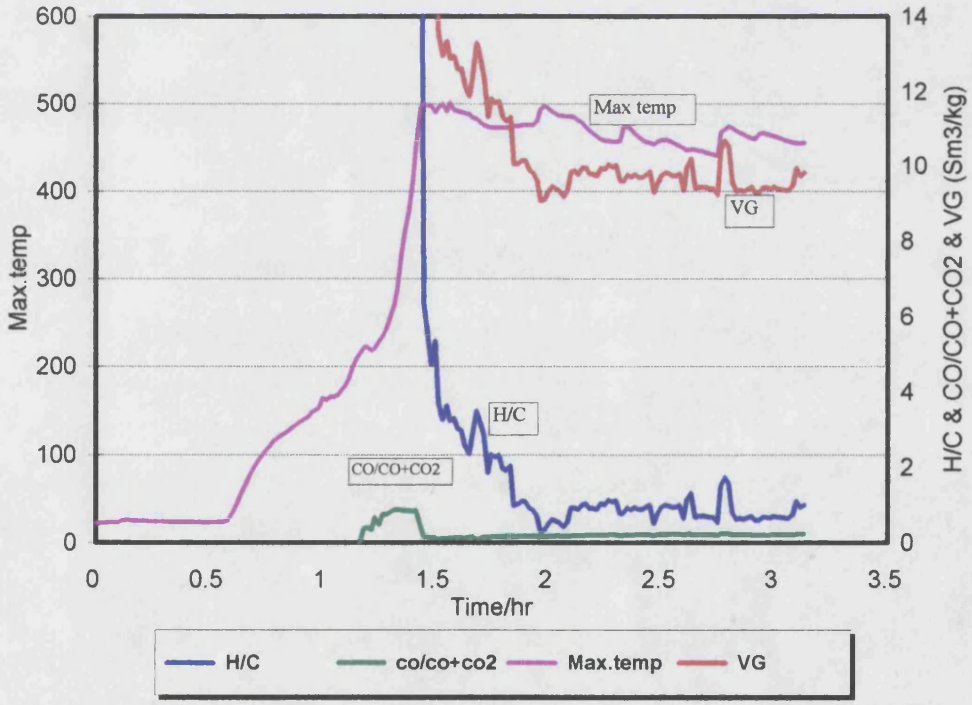


Fig 5.20 CO/CO+CO2, H/C and VG (volume of air required) - Run 4 - Clair oil.

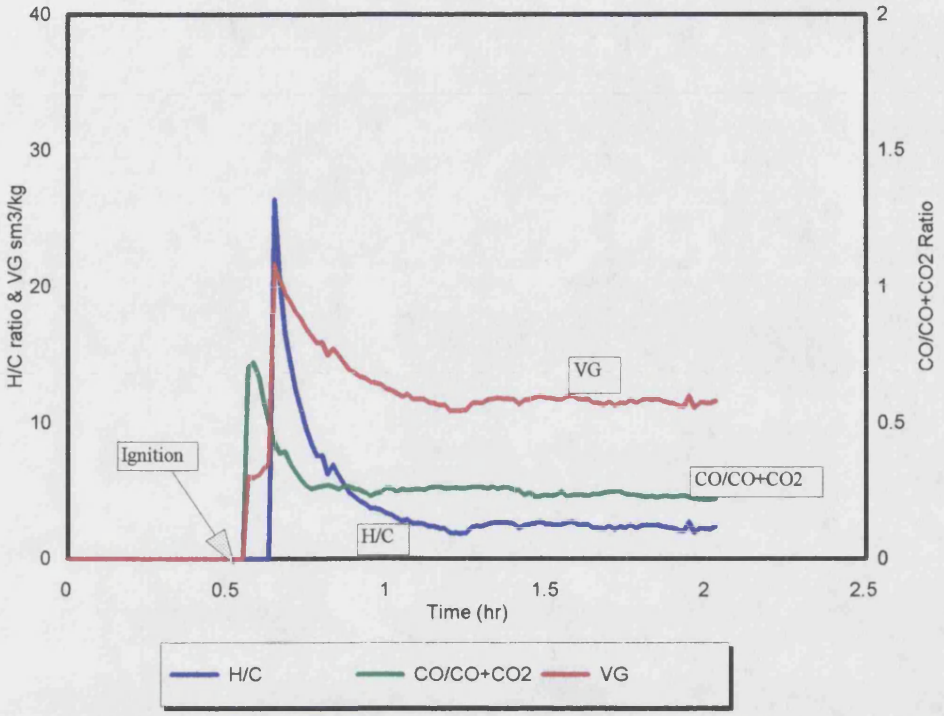


Fig 5.21 CO/CO+CO2, H/C and VG (volume of air required) Run 5,Clair oil

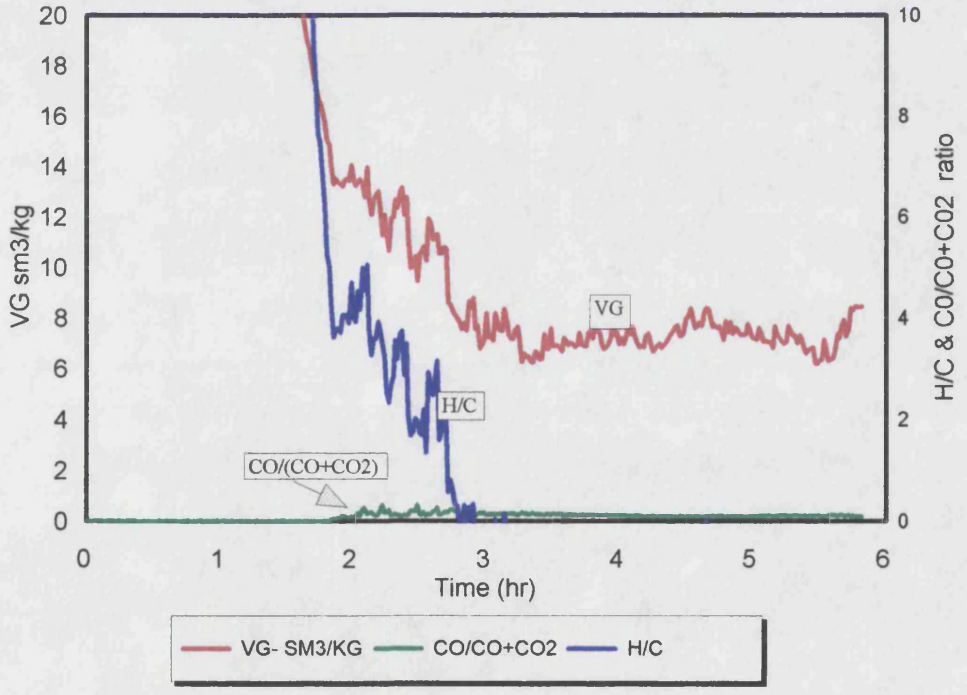


Fig 5.22 CO/CO+CO2, H/C and VG (volume of air required) Run 6, Clair oil

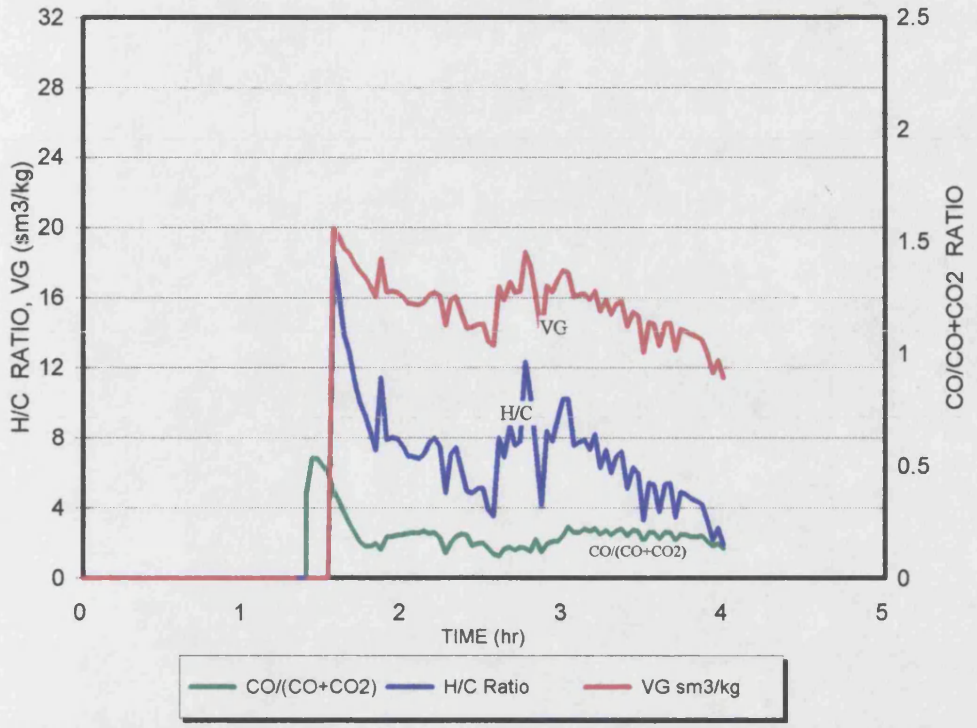


Fig 5.23 CO/CO+CO2, H/C and VG (volume of air required) Run 7, light oil.

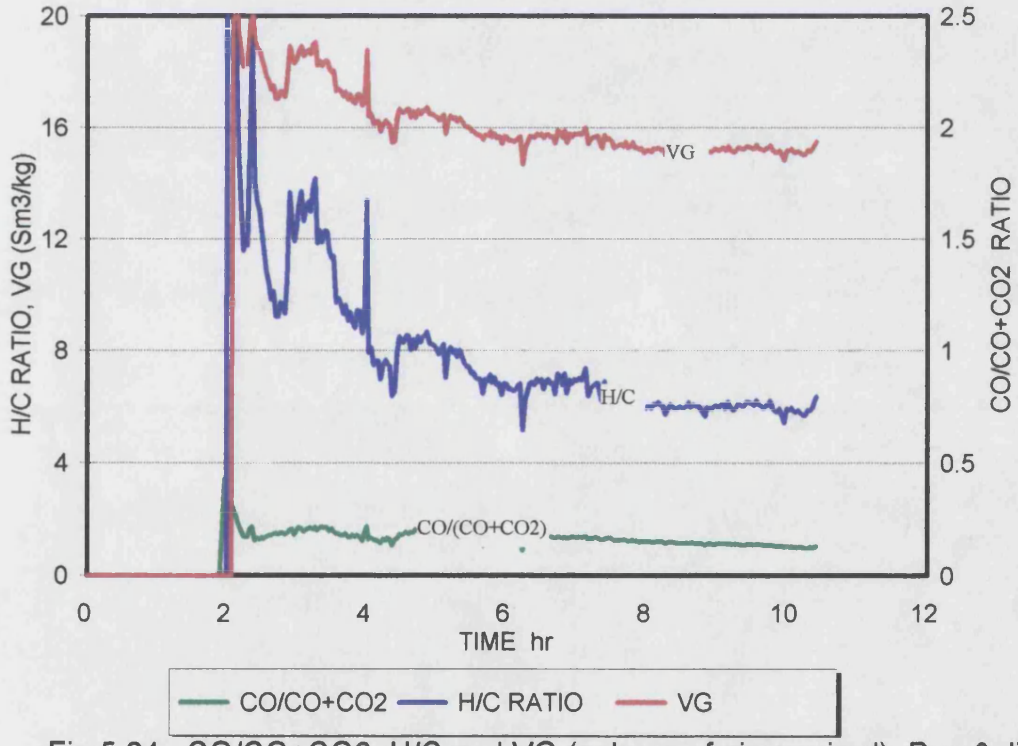


Fig 5.24 CO/CO+CO2, H/C and VG (volume of air required) Run 8, light oil

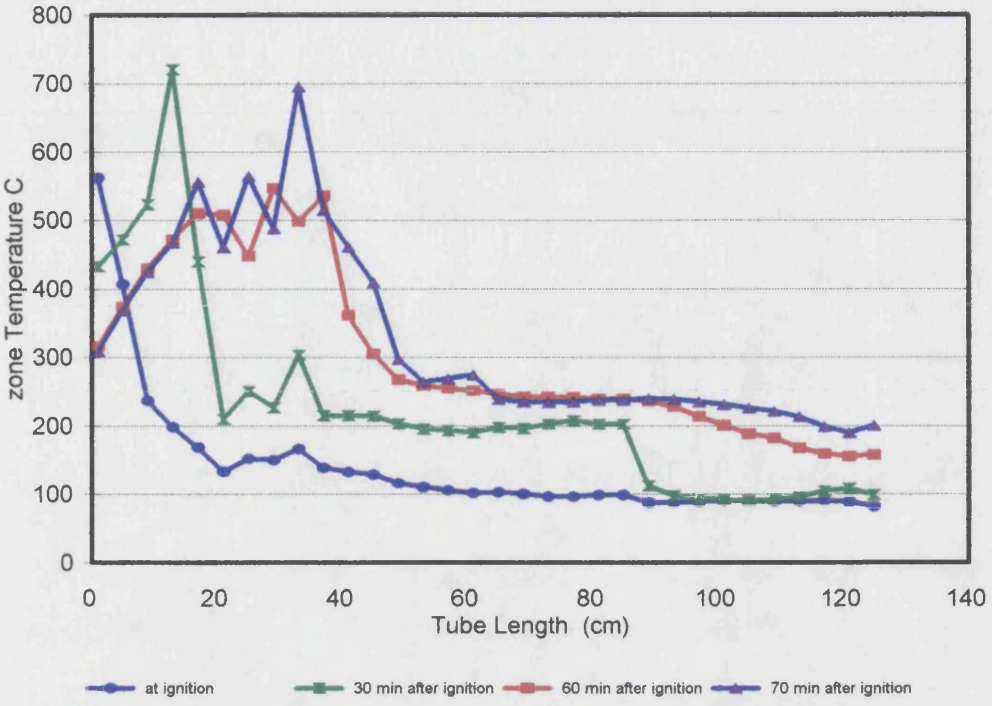


Fig 5.25 Sandpack Temperature profile along Combustion Tube (Run 3, Clair oil)

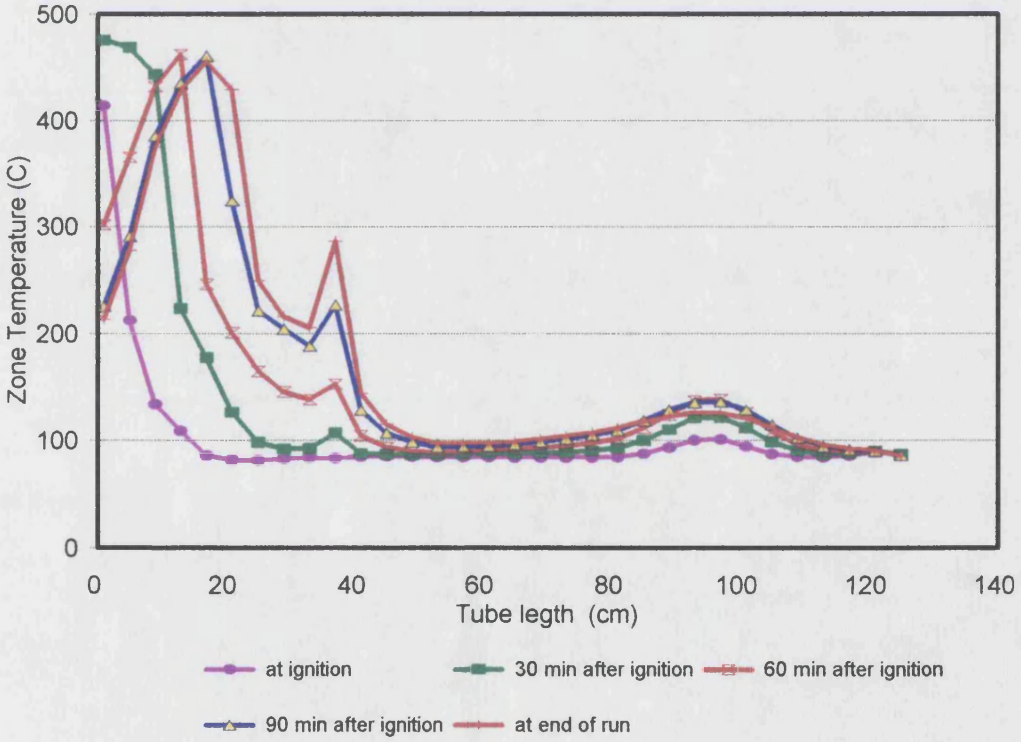


Fig 5.26 Sandpack Temperature profile along Combustion Tube (Run 4, Clair oil)

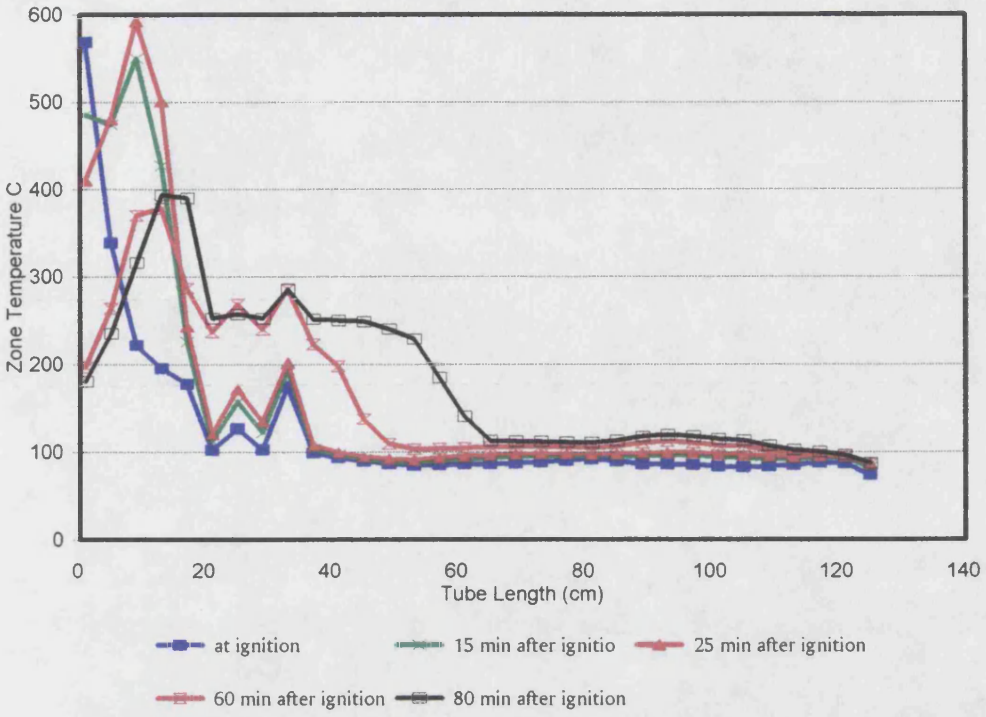


Fig 5.27 Sandpack Temperature profile along Combustion Tube (Run 5, Clair oil)

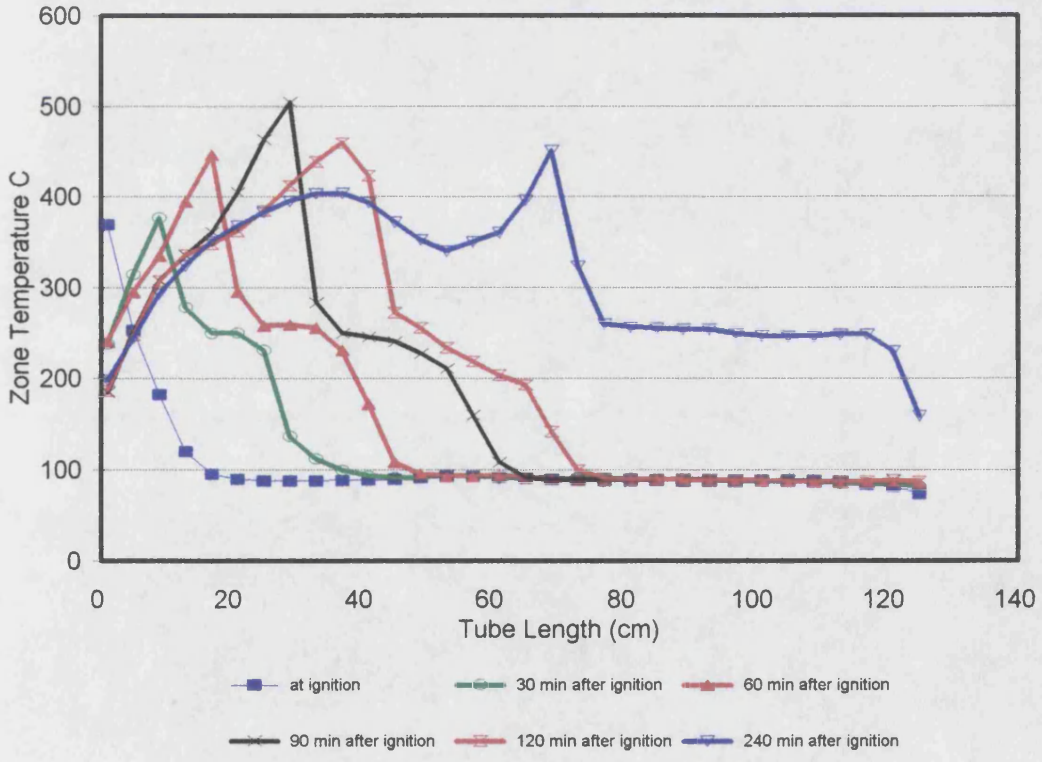


Fig 5.28 Sandpack Temperature profile along Combustion Tube (Run 6, Clair oil)

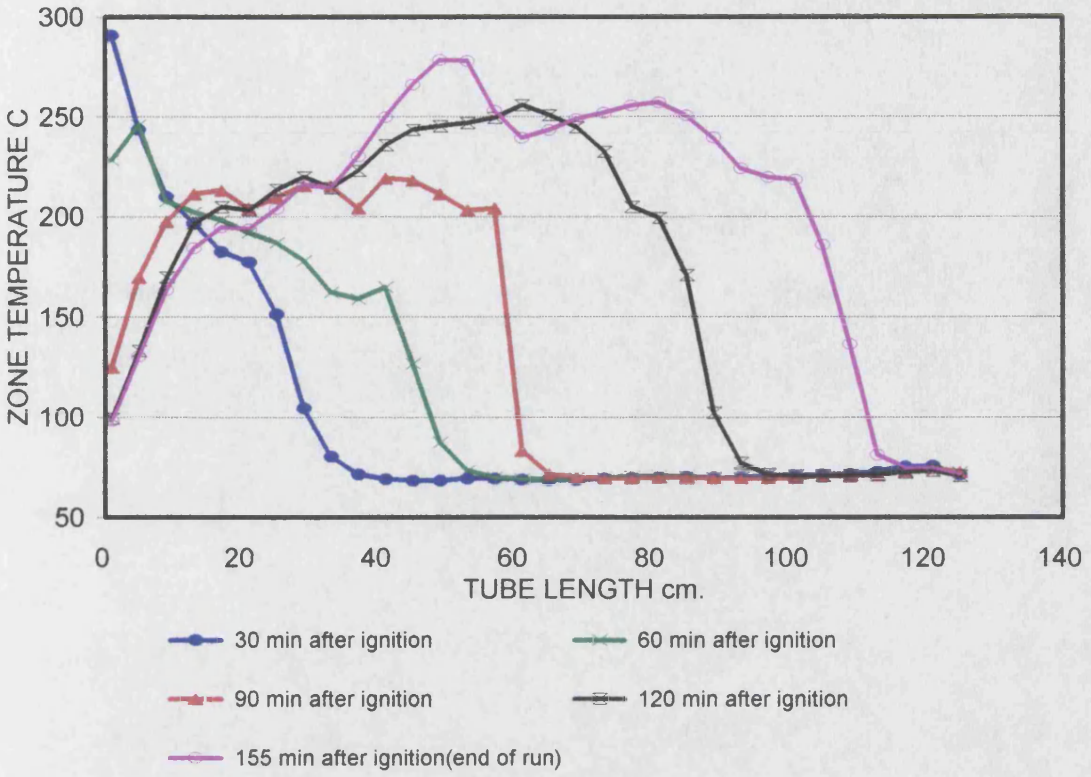


Fig 5.29 Sandpack Temperature profile along Combustion Tube (Run 7, light oil)

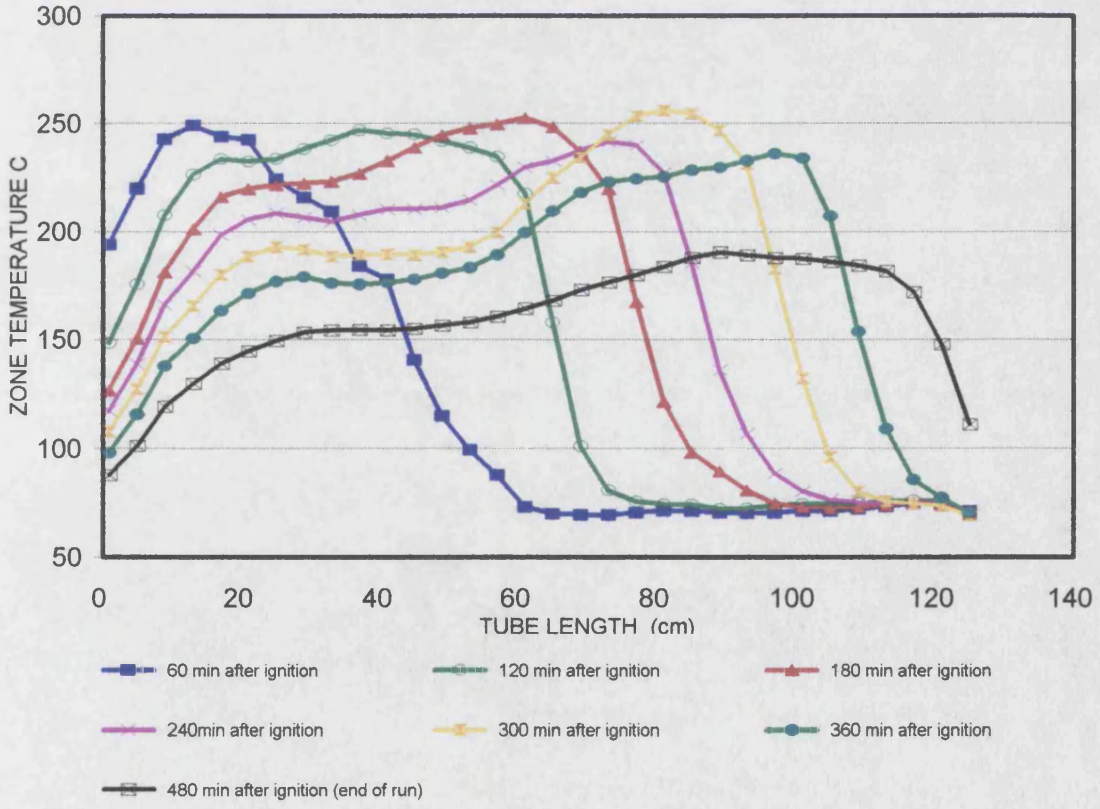


Fig 5.30 Sandpack Temperature profile along Combustion Tube (Run 8, light oil)

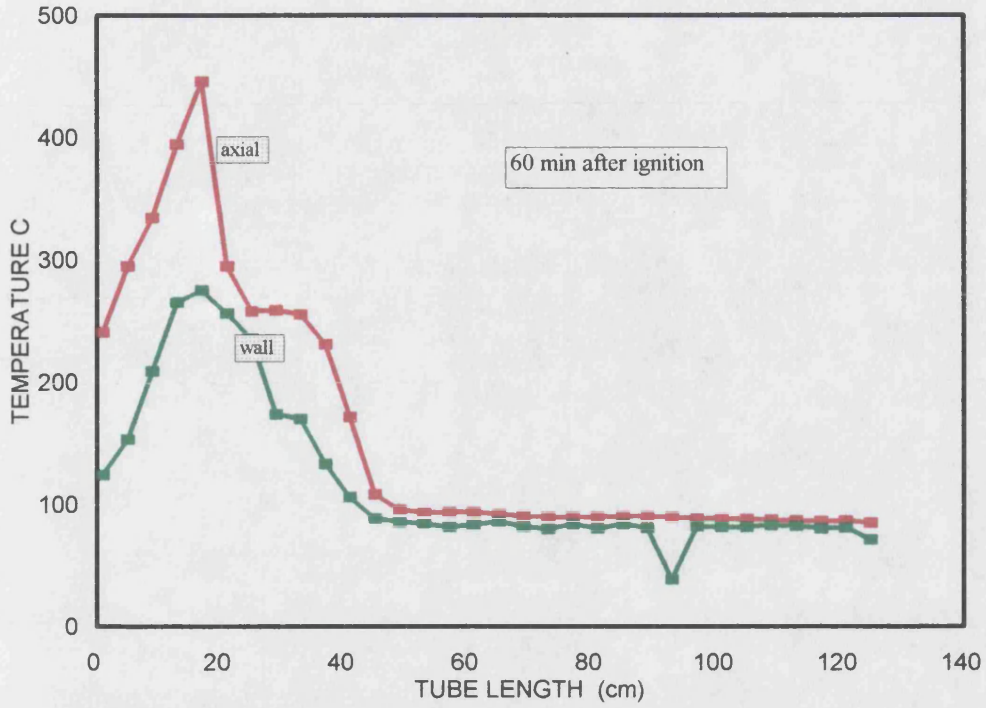


Fig 5.31 Axial and Wall Temperature profile (Run 6 - Clair oil)

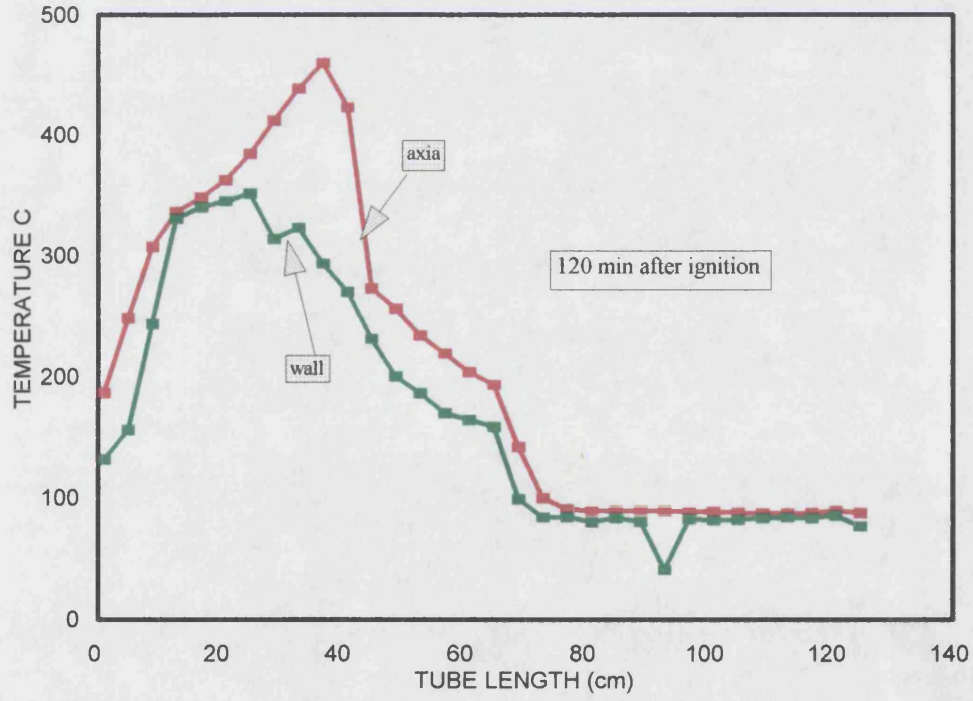


Fig 5.32 Axial and Wall Temperature profile (Run 6 - Clair oil)

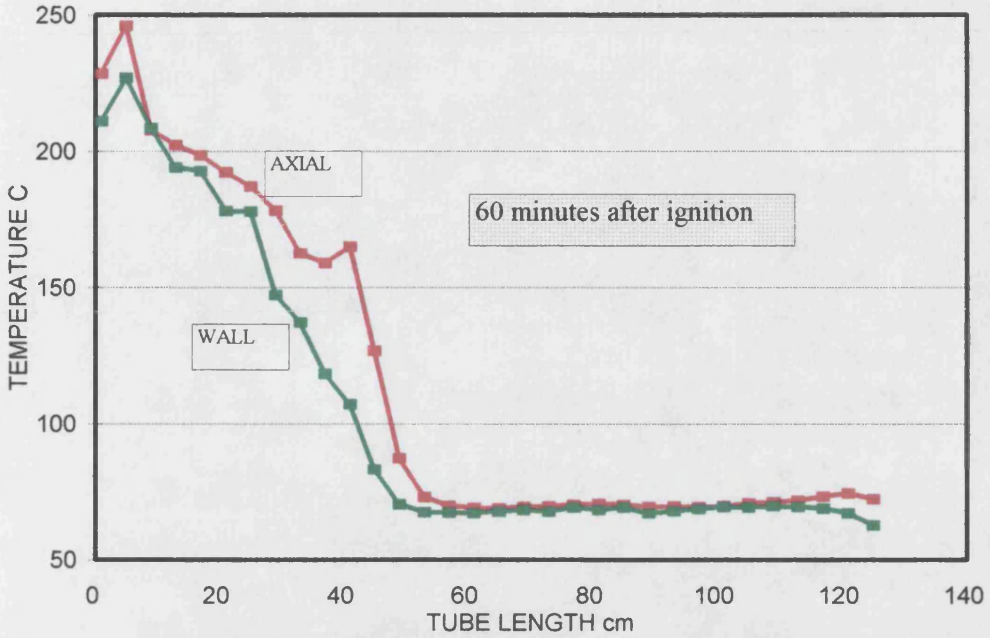


Fig 5.33 Axial and Wall Temperature profile (Run 7)

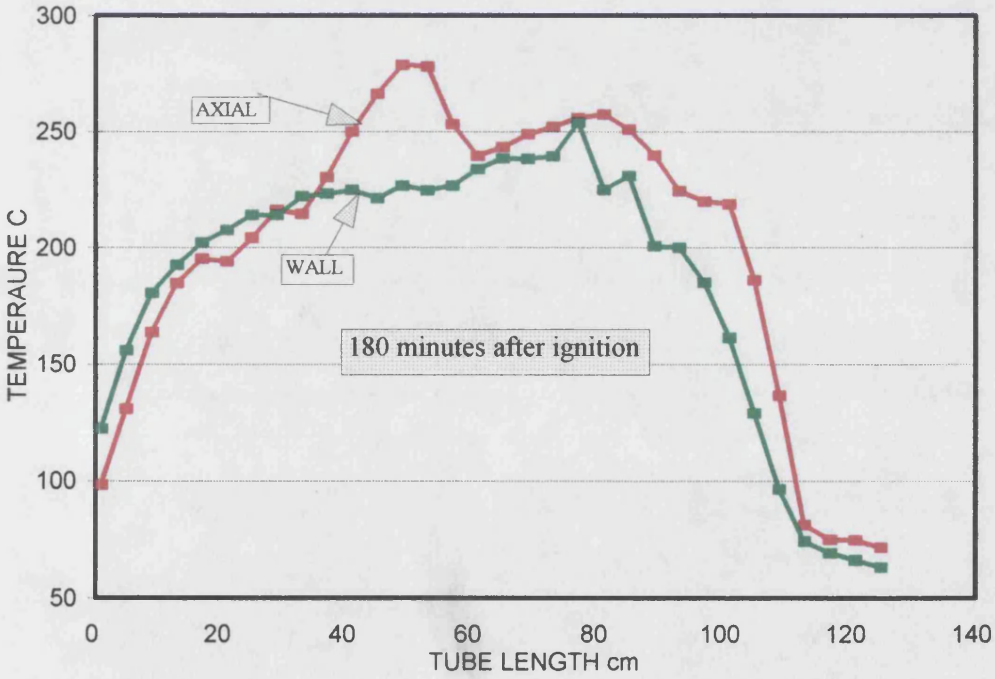


Fig 5.34 Axial and Wall Temperature profile (Run 7)

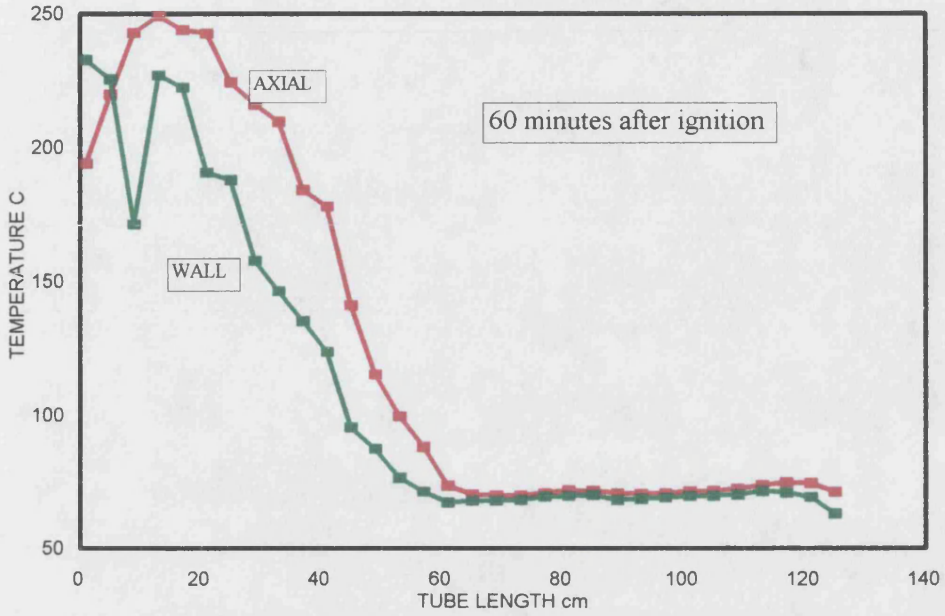


Fig 5.35 Axial and Wall Temperature profile (Run8)

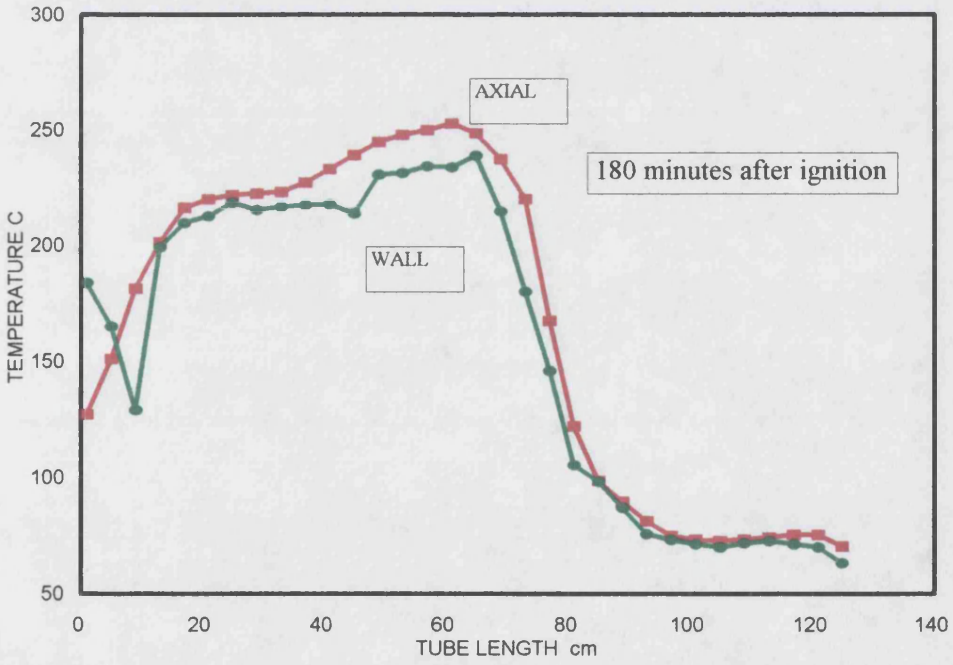


Fig 5.36 Axial and Wall Temperature profile (Run8)

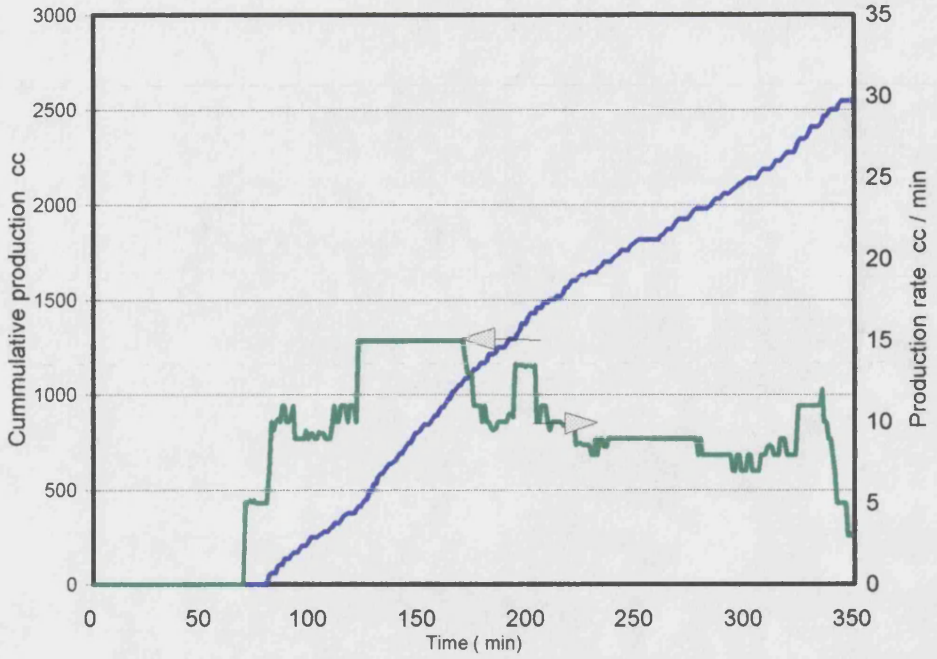


Fig 5.37A Cummulative and rate of produced liquid (oil + water) Run 6

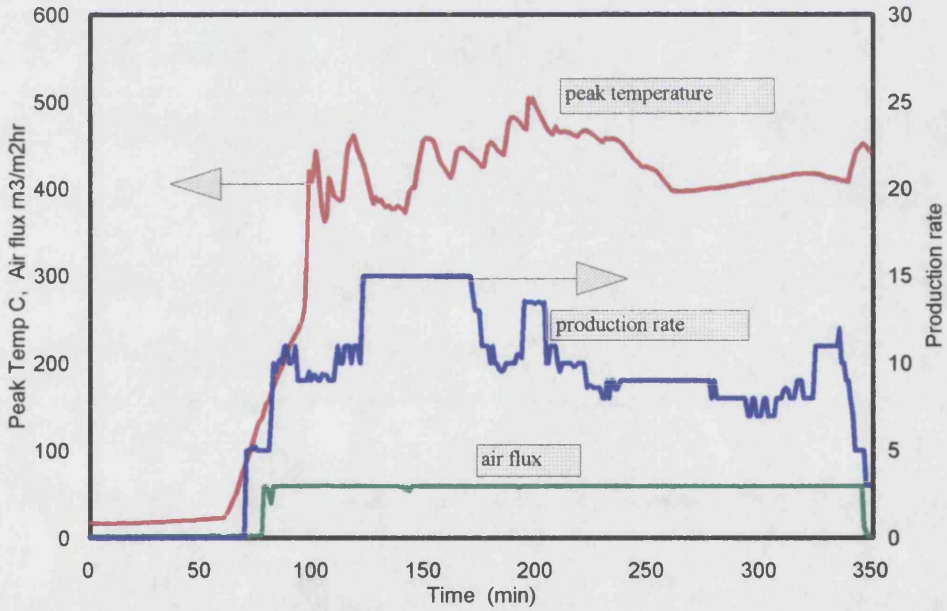


Fig 5.37B Liquid production rate, air flux and peak temperature profile (Run 6)

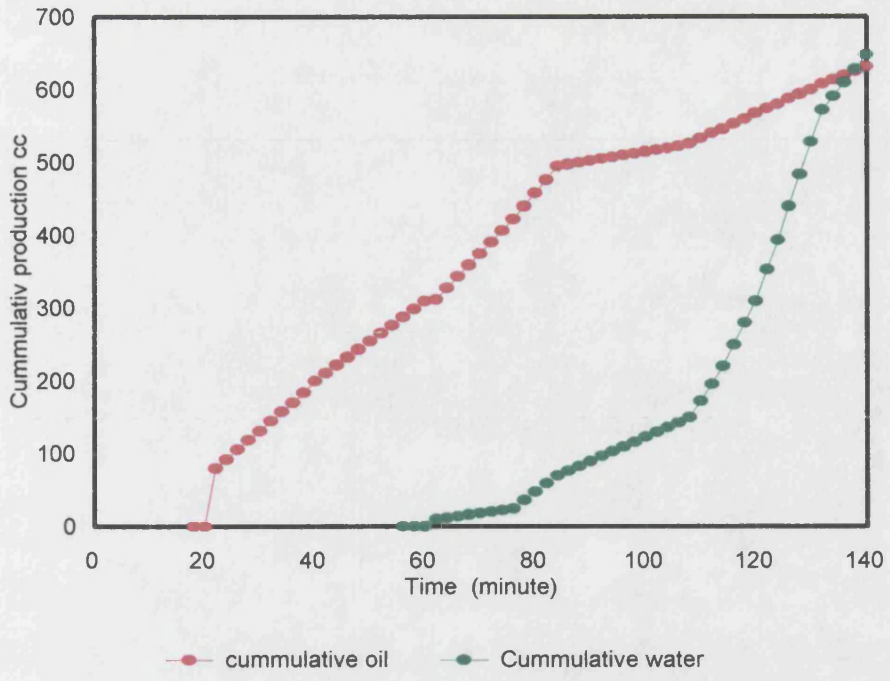


Fig 5.38A Cummulative oil and water production(Run 7)

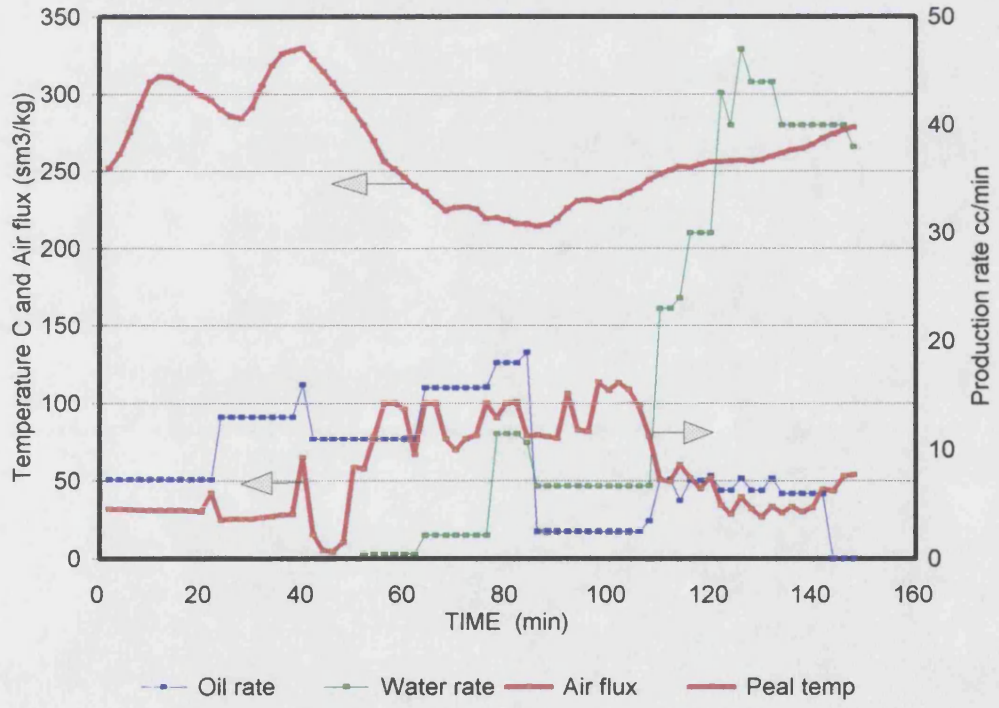


Fig 5.38B Liquid production rate, air flux and peak temperature profile (Run 7)

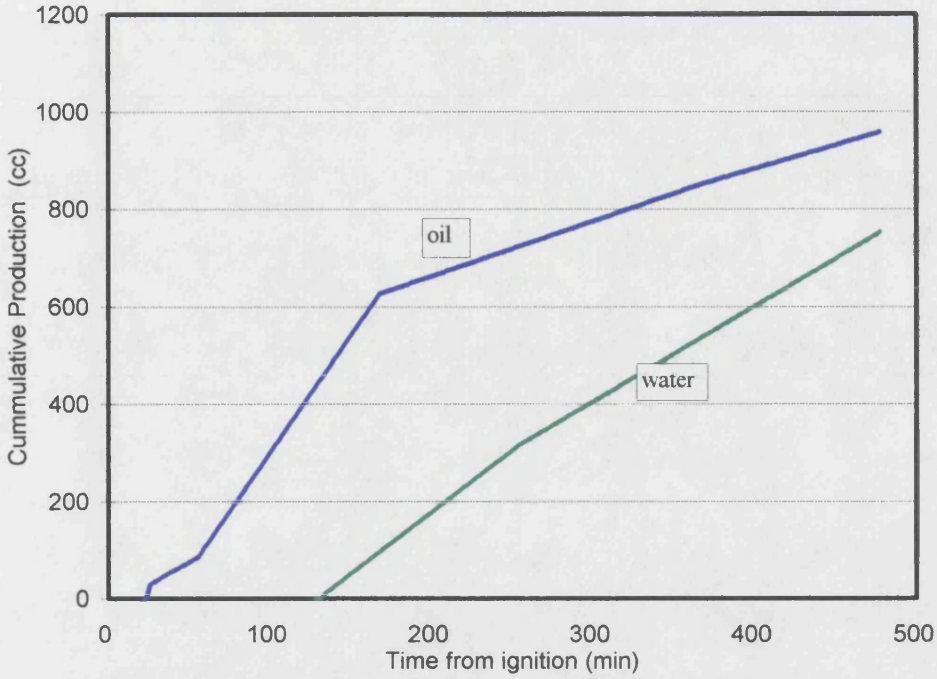


Fig 5.39A Cummulative oil and water production (Run 8)

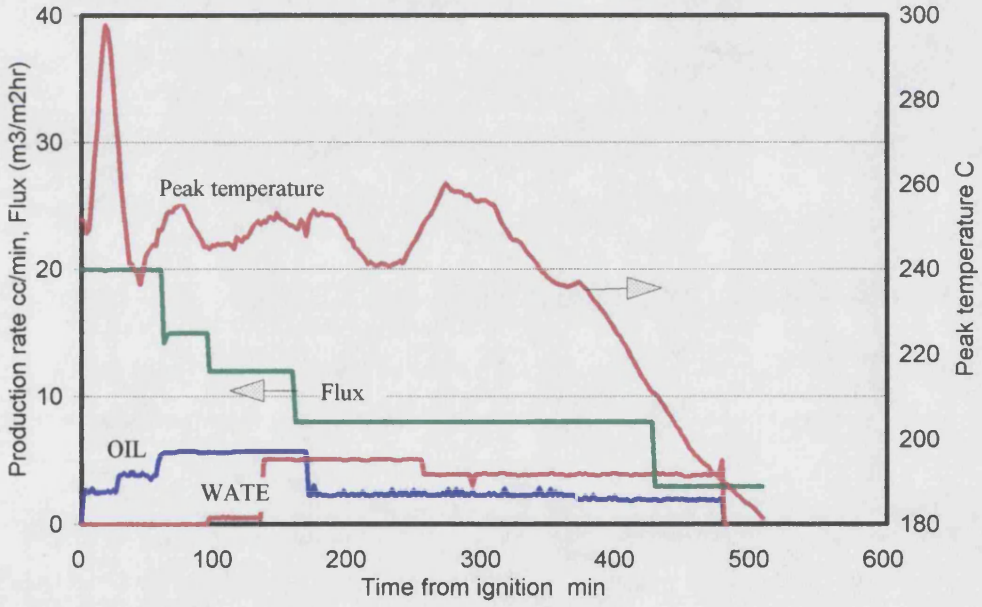


Fig 5.39B Liquid production rate, air flux and peak temperature profile (Run 8)

CHAPTER SIX

SIMULATION STUDIES

6 *Simulation Studies*

Computer simulation is used during all stages of an IOR project. It aids in the understanding of a particular process mechanism and is an essential part in the design, implementation and optimisation of a full field scale project.

The in-situ combustion process for enhanced oil recovery is extremely complex, because it involves many physical changes as well as chemical reactions taking place simultaneously or sequentially, either in the vicinity of the combustion zone, or down stream in the reservoir, Numerical simulation is therefore a powerful tool for studying such a complex process.

6.1 The simulation model

The construction of a numerical simulation model requires a considerable degree of sophistication and knowledge of several different areas of specialisation.
These are reservoir engineering principles, partial differential equations and computer programming. A simulator is an implementation of these disciplines in a computer model. The computer model is to be adequately capable of predicting physical reality, then physical results are needed to compare with.

The physical model of the process can be represented by a combustion tube, or 3-D cell experiments, which represent a 1-D or 3-D small scale section of the reservoir. A Mathematical model is based on the physical laws of mass and energy conservation and other constitutive equations, which describe the process and require to be solved simultaneously. The model is non-linear partial equations, chemical reactions equations and the properties of reservoir rock and fluids are represented in finite difference form, so that a numerical technique can be used to obtain an approximate solution to the equations.

6.2 Background

Due to the complexity of the in-situ combustion process and the limited information provided by the physical model experiments, considerable effort has been developed on numerical simulation of the in-situ combustion process, in order to obtain more understanding about the different aspects of the process.

These efforts were started as early as 1950's by Ramey(1959), Baily and Larkin(1959) and Baker(1962), who developed the earliest mathematical models. These models were concerned primarily with the heat transfer aspects. Most sophisticated numerical models came later, developed by **Chu(1964)**. His model was the first radial flow model for in-situ combustion. It considered the energy effects of vaporisation and condensation on the temperature distribution, but neglected the accompanying phase change by assuming a constant fluid saturation.

Gottfried 1965 developed a more comprehensive model, which considered multiphase fluid flow(gas, oil, water), heat generation and transfer. The simulator exhibited all of the major thermal and hydrodynamic characteristics of in-situ combustion process. The limitation in this model was, that gravity, capillary effects, coke formation or oxidation were not included

Smith and **Farouq Ali 1971** presented the first two dimensional in-situ combustion simulation model. This model accounts for heat generation in the combustion zone, heat transfer by conduction and convection and heat losses by conduction to the adjacent formation. **Farouq Ali 1977**, developed this model further by including the effect of capillary pressure and the solubility of gases in the liquids

Crookston et al 1979, introduced a three phase two dimensional simulator using a comprehensive mathematical formulation. Four chemical reactions are included. The model also included gravity and capillary effects, heat transfer by conduction and convection, vaporisation and condensation of both water and hydrocarbons.

The Computer Modelling Group of (CMG), Calgary, Canada developed a fully implicit combustion and steam flood simulator called ISCOM in 1979 by Rubin and Grabowski. This model includes four phase, variable number of oil components, variable number of chemical reactions, gravity and capillary pressure effects.

Coats(1980) also presented a numerical model for simulation of wet or dry, forward or reverse combustion in one, two or three dimensions. The model allows any number and identities of components, chemical reactions, products and stoichiometry.
Many more contributions have been made during the last ten years. These concentrate mostly on improving the simulators efficiency, such as computing time, dealing with input data and including more components and chemical reactions.

6.3 Simulation Objectives

In the first part of this project, a great deal of work was done to develop and operate the fully automatic high pressure combustion tube facility. Six successful experiments were carried out using both light and medium oils. The experimental results have provided a useful understanding of in situ combustion. The main objective of the simulation study is to investigate numerically the potential of in-situ combustion process at high pressure conditions, using both light and medium crude oil. The primary aim was to study the sensitivity of the process performance to various parameters in order to generate more understanding of the process aspects. In order to achieve this, the experimental physical model results are used to validate the simulation results. The results of this study along with the experiments results may then find useful application in the design and interpretation of in-situ combustion projects.
In this study a 1-dimensional simulation was carried out based on the combustion tube dimensions used in the experimental work. The simulation was performed using the STARS simulator as it is one the most advanced and comprehensive thermal recovery simulators.

6.4 The STARS Simulator

STARS (Steam Additives Reservoir Simulator) is the successor to ISCOM. It is a multidimensional, multicomponent and multireaction reservoir simulator developed by the CMG(Computer Modelling Group). It simultaneously solves the energy, mass and physical properties equations, which are translated to finite difference equations, which are in turn linearized to linear algebraic equations. Solutions are obtained for temperature, pressure, saturation, composition and liquid and gas rates, etc. Full details for operating STARS are contained in the STARS Technical Manual (User's Guides, CMG, 1996)

6.5 Input Data File

The input data needed to be inputted to the model must be good enough to illustrate the actual behaviour that takes place in a real reservoir. The following data is required:

6.5.1 Input / output control

This defines the parameters that control the simulator's input and output activities. The input units are specified as field units, while the output units are specified as laboratory units. The simulator is told which outputs to calculate, i.e. temperature, pressure, oil, water, gas rates and saturation, etc.

7. 5. 2. Reservoir description:

This section contains the physical description of the reservoir, such as the proposed dimensions of the simulation (1D, 2D, or 3D), the number of grids and their size, and the rock properties(e.g porosity, permeability, rock thermoconductivity etc). Reservoir description data are given in Table 7.1. The simulation combustion tube as it is shown in Fig 6.1 has same dimensions as the experimental one.

Table 6 - 1 Reservoir and Rock properties

Grids number	**32**	**64**	**128**
Grid size (ft)	**0.128**	**0.064**	**0.032**
porosity (W150) %	**45**	**45**	**45**
porosity (W50) %	**36**	**36**	**36**
permeability (W150) md	**616**	**616**	**616**
permeability (W50) md	**1004**	**1004**	**1004**
rock heat capacity Btu/ft3-F	**35**	**35**	**35**

W50 = Coarse Sand, W150 = Fine Sand

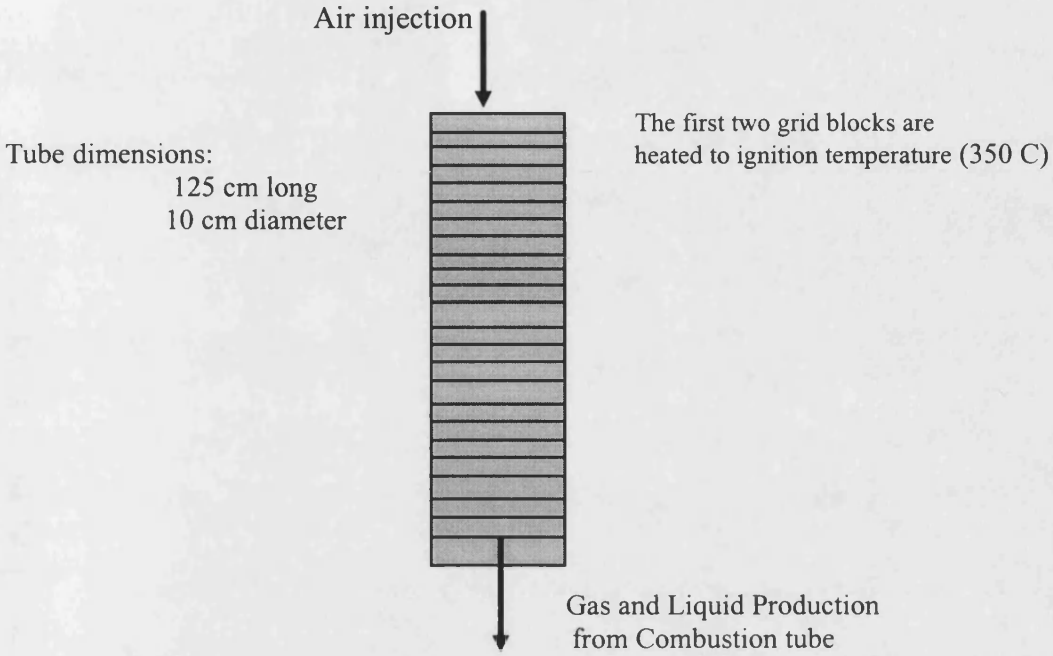


Fig 6.1 Combustion Tube Grid representation

6.5.3 Fluid definitions

The number of components and their physical properties are required. The chemical reactions (reaction involved, Arrhenius constants, enthalpies, K-values and stochiometric coefficients) all must be specified here. Three hydrocarbon pseudo components: C1-C5, C6-C10, $C11^{+}$ have been chosen to represent gas, light and heavier oil hydrocarbons fractions, respectively. Fluid properties are given in next Table 6.2

Table (6 - 2) Petroleum fluid pseudo component definition.

Pseudo component	M. W.	Pc psi	Tc K°	mole fraction (medium oil)	mole fraction (light oil)
1- H_2O	18	3155	705	0.000	0.000
2- C1-C5	72.15	488.1	385.47	0.0687	0.2919
3- C6-C10	115.98	363.09	548.2	0.1775	0.2655
4- $C11^+$	329.36	196.9	1478.9	0.6738	0.4025
5- CO2	44.01	1071	87.56	0.000	0.000
6- CO	28.01	507.5	220.78	0.000	0.000
7- N2	28.01	500	232.84	0.04	0.04
8- O2	32	730	181.72	0.000	0.000
9- Coke	-	-	-	-	-

Fluid property data supplied by TINGAS, 1998.

The light oil mole fraction is for a typical light oil (39 API)

Assume gas in the tube at the initial condition is N2 (4%) with a small concentration of C1-C5 at equilibrium condition with the liquid petroleum phase.

In this study the fluid composition is defined as a nine component mixture. The kinetic rate constants, Arrhenius constants, improved K-value equilibrium data, and some other properties were supplied by Tingas (1998). Modifications and improvements which have been made to the basic input file are mentioned in the section on modification and validation .

Reactions

The specific reaction rates were assumed to be represented by the Arrhenius equation:

$$k = A\, e^{(-E/RT)} \qquad (6.1)$$

where; k = specific reaction rate, A = Arrhenius constant, E = activation energy

The following chemical reactions have been used to represent the reactions occuring at different stages of the combustion process.

CHEMICAL REACTION 1: Cracking
$C11^{+} \longrightarrow C_6 - C_{10} + Coke$
CHEMICAL REACTION 2: Cracking
$C11^{+} \longrightarrow C_1 - C_5 + Coke$
CHEMICAL REACTION 3 Heavy oil burning
$C11^{+} + O2 \longrightarrow H_2O + CO + Energy$
CHEMICAL REACTION 4 light oil burning
$C_6 - C_{10} + O2 \longrightarrow H_2O + CO + Energy$
CHEMICAL REACTION 5 Hydrocarbon gases burning
$C_1 - C_5 + O2 \longrightarrow H_2O + CO + Energy$
CHEMICAL REACTION 6 Coke burning
$Coke + O2 \longrightarrow H_2O + CO + Energy$
CHEMICAL REACTION 7 Carbon Monoxide Burning
$CO + 0.5O2 \longrightarrow CO2 + Energy$

6 - 5 - 4 . Rock and fluid data

The type of fluid in the pores of the reservoir, as well as the relative permeabilities are defined in this section. The compressibility of the reservoir rock is taken as $7.3*10^{-7}kpa^{-1}$ The thermal expansion of the rock and the capillary pressure were assumed to be zero although neither will be zero in practice. The rock was assigned a heat capacity of 35 Btu / ft^3-F(Tingas 1998).

No temperature or capillary pressure dependence effect on relative permeability is used in the simulation runs. Relative permeability data used in this study is given in Table 6.3.

Table (6 - 3) liquid and gas relative permeabilities. (Sakthikumar - 1995)

SW	Krw	Krow	Sl	Krg	Krog
0.31	0	1	0.31	0.49	0
0.3323	0.0037	0.8869	0.43	0.3344	0
0.3545	0.0104	0.7784	0.59	0.1722	0.0008
0.3768	0.0191	0.6747	0.714	0.0844	0.0482
0.3992	0.0284	0.576	0.836	0.0276	0.2577
0.4215	0.041	0.4828	0.9591	0.0017	0.7513
0.4438	0.0539	0.3951	1	0	1
0.4662	0.068	0.3136			
0.4885	0.083	0.2335			
0.5108	0.0991	0.1707			
0.5332	0.116	0.1109			
0.5554	0.1339	0.0603			
0.5777	0.1525	0.0213			
0.6	0.172	0			
0.68	0.2479	0			
0.76	0.3325	0			
0.84	0.425	0			
0.92	0.5247	0			
1	0.6313	0			

6. 5.5 Initial conditions:-

Initial conditions such as pressure, temperature, oil, gas and water saturation are specified in Table 6-5 which shows the data used in this study.

Table: (6 . 4) Initial condition data

	Light oil (Australian-38.78API°)	Medium oil (Clair -19.8API°)
Initial water saturation Swi %	50	35
Initial oil saturation Soi %	45	60
Initial gas saturation Sgi %	5	5
Reservoir temperature (C)	80	63
Reservoir pressure (bar)	70	100

6. 6 . Validation of the simulation Model

Since the behaviour of the in-situ combustion process is very complex, a simulation model can only be validated based on certain criteria. There are a number of adjustable parameters one may adjust in order to obtain proper match. The most important parameters considered in this validation are:

(1) The temperature profile, this is the only internal state information measured experimentally. (2) The combustion front velocity. (3) Gas production and composition. (4) Production rates of oil and water.

6. 7 Simulation Trouble shooting and modifications.

The geometry system used in the model, was aligned with the combustion tube used for the experiments (see Fig 6.1). The combustion tube is cylinder 125cm long with 10 cm in diameter. The vertical combustion tube was ignited at the top. An external heat source was used to raise temperature in the first three grids up to an ignition temperature of 350C. Air was then injected continuously to sustain and propagate the combustion front toward the other end of the tube. Gas and liquid production were collected at the bottom end of the tube. The tube was simulated using two different sets of grids (64 and 128 grid blocks).

In order to simplify the process, a number of important assumptions were made. The model reservoir assumed to be homogeneous. Porosity and permeability were assumed to be constant in all directions

The first step was to establish a reasonable temperature and production profile. An input file provided by Tingas 1998, originally for modelling light oil reservoirs, was used as stepping stone. The initial condition data in Table 6.4, was used to make an initial run . The main observation from this run was, that oil production started as soon as the simulation commenced. The oil production rate increased sharply in the early period of the simulation and started to decrease. Also, in the simulation, air was injected right at the start of the run, while in the experiment, air is injected only when the ignition temperature is reached. It also took a long time to raise the temperature, but it did not exceed 200 C. This was because of the cooling effect

occurring whilst injecting the air. The input file was studied and further modifications were done on the time of heating and starting air injection.

Further simulation runs were done and a substantial progress was achieved in terms of the temperature achieved and slow down of oil production. On the other hand, oil production rate was still relatively high compared with the experiment. After further investigation, it was appeared that, the relative permeabilities appeared to have a great effect on the liquids movement and its distribution along the tube. This effect is discussed later in the section of the relative permeability effect.

This relative permeability not only affects the oil production rate, but also the oil saturation in sandpack, which in turn affects the fuel availability and combustion condition. Due to the absence of specific or measured relative permeability data for the light crude used in this study (Australian light oil), data obtained by Sakthikumar(1995) for similar light oil in-situ combustion study, was used Table (6-3). Using this final adjustment, a reasonable production history match was achieved. Some modifications were also made to the activation energy parameter in order to stabilise the reaction rate and adjust achieved values of the CO/CO2 ratio. On reaching this stage , the final version of the simulation input file, which included all modification was achieved in the simulation Run-8 of light oil. This run was then used as base case, and all the comparisons in the sensitivity study refer to this.

6. 8 Simulation results and discussion

Validation

In order to carry out the validation, the simulation runs were performed at the same initial conditions as those for the experiments. These conditions included the same air flux, operating pressure, bed temperature, ignition temperature and oil, water, and gas saturations. For validation, attention was concentrated on the temperature profiles as this is the most important internal state parameter for the process, as well as the liquid and gas production profiles.

6 . 8 .1 Temperature profiles and combustion front.

Experiments 8 was simulated. The main results for both the experiment and simulation are illustrated in Tables (6-5 to 6-8). Temperature profiles can be seen in fig 6.2 and 6-3. The light oil experiments,Run-8 and simulation Run-8 both failed to achieve a temperature higher than 255 C (The high rise in temperature at the beginning of runs is due to the effect of ignitor). Thus the process is classified as LTO reactions. The simulation runs took 5 minutes to get ignition from starting injection, while in experiments it took 10 to 15 minutes. Ignition time was found to be dependent on the ignitor temperature reached and gas communication inside the tube. The experiment results, Fig 6.2, shows a stable peak temperature at around 250 C, over the experiment time. However, the simulation, Fig 6.3, predicted same value of temperature over the first 400 minutes of the run time, then a variation of about 30 C, was observed . This is mainly because more oil was predicted to be produced in the simulation than in the experiment at the early stage of the run. This affected the oil saturation along in the sandpack, leading to a decrease in the temperature as the combustion front moved further down the tube. There was less good agreement in the combustion front velocity between experiments (16.3 cm/hr) and simulation (8.4cm/hr).

The simulation of medium Clair oil Run-6, (Fig 6.5) showed a stable combustion temperature of around 400 C^{o}, compared to 450 C achieved in experiment, Run-6 (Fig 6.4). There was also reasonable agreement in terms of combustion front velocity between experiment and simulation , where it was 20 and 13.6 cm/hr respectively.

The simulation temperature profile along the tube (Fig 6.6), shows a stable temperature front movement along the tube, whilst in the experiment (Fig 6.7) there were a few temperature peaks which developed along the tube, that could be related to the fuel distribution in the sandpack.

Simulation failed to predict the steam plateau ahead of the combustion zone in both cases of medium and light oil, while there was distinctive steam zone in experiments especially with medium oil (Run-6).

Table 6.5 Predicted Temperature and combustion front velocity [Run 8 - light oil]

RUN	AIR FLUX m3/m2hr	TIME TO GAS BREAKTHROUGH (min)	STABLE COMBUSTION TEMPERATURE (C)	COMBUSTION TIME (min)	COMBUSTION FRONT VELOCITY (cm/hr)
Experiment Run-8	20 -8	from beginning	250	330	16.2
Simulation Run-8	8	51	235	889	8.4

Table 6.6 Predicted Temperature and combustion front velocity [Run 6 - medium oil]

RUN	AIR FLUX m3/m2.hr	TIME TO GAS BREAKTHROUGH (min)	STABLE COMBUSTION TEMPERATURE (C)	COMBUSTION TIME (min)	COMBUSTIONFRONT VELOCITY (cm/hr)
Experiment Run 6	60	from beginning	450	247	20
Simulation Run 6	60	12	425	308	13.6

7 . 8 .2 Oil and water production

The main observation concerning the production profiles was that, in all simulation runs production started as soon as simulation commenced, before the ignition temperature was achieved as shown in Figs 6.11. However, in the experiment, the production started at ignition or shortly afterward see Figs6.10 .

As can be seen in Fig 6.11 for the light oil(Run-8) the simulation predicted a high initial oil rate from time zero, which then decreased to a low level and then levels off at a more or less constant rate. The liquid initial rate seen in the simulation did not occur in the experiments. Water production in the experiment was delayed after starting oil production, which confirms to the simulation. Toward the end of the simulation, the water oil ratio is very high and exceeds that observed from the experiments. This difference in production profiles is related to the connectivity inside the tube.

From the experimental results, it was observed that breakthrough of gas began as soon as air injection was started. This was due to high gas communication existing inside the tube. On other hand, in the simulation the communication was not as high as in experiment, and the gas takes a certain time to breakthrough, depending on the air flux. Before a certain level of gas communication is established, most of the injected air which neither reacts nor dissolves in the oil, gathers behind the front, acting like a piston and accelerates the liquid displacement. A trial was made to improve the gas communication by increasing the initial gas saturation inside the tube, but this did not affect the production rate nor the gas communication. The absence of specific (measured) relative permeability data might also be responsible for not accurately simulate the actual oil relative permeability inside the tube.

Table 6 .7 - Liquid and Gas production [Run- 8, Australian light oil]

	Experiment Run 8	Simulation run 8
OOIP (ml)	1600	1600
OWIP (ml)	1770	1770
oil recovery (ml)	959	1228.3
water recovery (ml)	747	1433.4
oil recovery (%)	64	88.7
water recovery (%)	43	81
CO2 %	6.5 - 8.3	14
CO %	1.4 - 2.5	2
O2 %	2.7	0.0

Table 6.8 Liquid and Gas production [Run-6 medium heavy Clair oil]

	Experiment 6	Simulation run 6
pressure/ bar	100	100
soi %	60	60
swi %	35	35
IOIP ml	2120	2120
IWIP ml	1240	1240
oil recovery %	83	90
water recovery %	58	100
CO2 %	15.2	14.3
CO %	5	3
O2 utilisation %	77 - 91	100

6 . 8 .3 Gas production and saturation profiles.

Gas production results from simulation and experiments can be seen in Table 6-7 and 6-8. As it can be seen in gas production profiles in Fig (6.3) and Fig(6.5), the levels of carbon oxides gases produced in the simulation were higher than what was obtained from the experiments Figs 6.2 and Fig6.4. It is noticed that there is a peak in carbon monoxide initially, which did not occur in the experiments. This signifies that substantial LTO reaction was occurring upstream of the ignition region even before the ignition temperature was reached. However, this reduced rapidly soon after ignition was confirmed.

A main observation from the simulation runs, is that 100% oxygen utilisation is predicted, which is not the result achieved in the experiments, where it was between 29% and 94%., therefore, relatively low CO2 levels were produced from Run 7 and 8 ranging between 6.5 and 8%. compared to around 12 to 15% from simulation.

The low oxygen utilisation levels observed in experimental Runs7 and 8 using Australian light oil corresponded to the periods of high flux and because of the limited amounts of fuel available. However, when the injected air flux was reduced the oxygen utilisation improved and reached up to 94%. On the other hand, in the simulation, which used a lower flux from the start, together with the assumption of a homogeneous reservoir matrix caused gas breakthrough be delayed, thereby improving oxygen utilisation.

7 . 8 . 4 Bed saturation.

The predicted fluid saturation inside the tube is illustrated in Figures 6 .12 to 6.15.

As soon as the temperature was raised too 200 C upon air injected, the oil saturation in the ignition zone started to change dramatically especially for light oil(Fig 7.15).

The rapid decrease in oil saturation in the zones adjacent to the combustion front is due to the volatile light fractions had being vaporised and displaced down stream.

Oil saturation in the steam zone is around 10%. Whilst in the experiments, oil saturation in steam zone was found to be around 15 to 20%. At early combustion time, a classic fluid distribution is observed in the tube (combustion front, steam zone, oil bank and virgin zone Fig 6.12).

It is noticed that the oil saturation is reduced at a much faster rate than water saturation. This understandable with light oil which characterised by high volatility and also some effect of partial miscibility of CO2, aiding oil production. Some water (up to10%) in steam state, stays behind the combustion front. This because the front needs less time to burn the fuel and consequently move ahead of the residual steam because there is not enough heat to vaporise all of it.

6 - 8 -5 Molar fraction of pseudo components.

Pseudo components fractions distribution along the tube at various combustion time is shown in Figures 6.16 to 6.18. As the bed is heated, the lighter oil fraction (C1-C5) are first observed in the very adjacent area to the combustion front. When the air injected, a part of light fraction was burning to produce carbon monoxide even before ignition temperature was reached. As ignition was initiated and combustion front was formed, it pushed the whole light fraction ahead of it. The oil fraction present in the combustion zone was mostly $C11^{+}$, which represents the combustion fuel especially in light oil when very little or no coke was observed to be formed. The main effect is an of slightly reducing levels of (C1-C5), (C6-C10) and $C11^{+}$ with increase combustion time, but otherwise, there distribution ahead of the combustion front remains relatively constant.

6 - 9 Sensitivity study [Run 8]

6 - 9 -1 Effect of Grids Block Size

It is important to chose a grid block size which gives sufficiently accurate results. The main concern in choosing the grid size is the extent of numerical dispersion.

A larger grid block size may cause a too large an approximation, or error between adjacent blocks , seriously affecting the accuracy of the whole process.

This effect was tested using 32, 64 and 128 blocks in the simulation as shown in Fig. 6.19 and 6.20 and summarised in Table 6.9. Reducing the number of grid blocks from 128 to 64, extended the combustion time to 107 minutes, causing a slight reduction in the front velocity.

The simulation calculation time, increased with the increasing number of grids. The run of 64 grids lasted (7 minutes) one fifth of the 128 grids run time(34.3 minutes), while the 32 grids run lasted (3.3 minute) only one tenth of that time, in the order, 5 times for 128 vs. 64 grids and 10 times for 128 vs. 32 grids. The temperature profiles Fig 6.19, show close agreement in temperature in the stable peak combustion during the early combustion period, but then wide divergence at later times, up to 50 C.

Liquid production decreased by increasing the grids number from 64 to 128 by 5% for oil and 9% for water.

Table 6-9 Effect of grid block size - Combustion and recovery results

Number of Grids block	128	64	32
flux m3/m2.hr	8	8	8
Combustion time (min)	693	800	852
Front velocity (cm/hr)	10.36	8.4	8.2
Combustion temperature C (stable period)	235	235	235
CO2 %	14	13.8	14
CO %	2.5	2.2	2
O2 utilisation %	100	100	100
oil recovery %	86	91.3	90.8
water recovery	75.4	84.3	91.6

6 - 9 -2. Effect of air flux

The results at different air fluxes from 8 to 30 m^3/m^2hr is shown in Figs 6.21 and 6.22 and Tables 6.10 and 6.11. The main effect of using high flux of 30 m^3/m^2hr is the considerable reduction in the duration of the combustion. Overall, the large change in flux, almost 4 fold, does not appear to affect the peak temperature due to the limited amount of fuel available for combustion. On other hand, combustion front velocity appeared to increase almost in proportion to the increase in air flux, as shown in Table 6.10. Figure 6.22 shows that, the produced CO2 and CO are not appreciably affected by the change in air flux during the combustion stable periods.

Table 6.10 : Peak temperature and Combustion front velocity at different air fluxes[ligh oil Run 8].

Flux m3/m2hr	30	15	8
Time to gas breakthrough (min)	12	27	50
Combustion time (min)	231	467	889
Combustion temperature C av	241	231	235
Combustion Front velocity (cm/hr)	32.46	16.06	8.4
CO2 %	14	13.85	13.8
CO %	2	2	2.2
O2 utilisation %	100	100	100

Table 6.11 Oil and Water recovery at different air fluxes [light oil Run 8].

Flux m3/m2hr	30	15	8
OOIP	1600	1600	1600
OWIP	1770	1770	1770
oil recovery %	88.8	86	89.8
water recovery %	98	81	82

6 - 9 -3 Step time

The choice of time step is important, as it affects the simulation stability and accuracy of the calculation. A smaller time step was found to be better. A trial, using a bigger time step (0.5 minutes or larger) resulted in instability in the calculation, leading to simulation failure.

6 - 9 - 4 Initial Oil Saturation

Run-7 and 8, which were carried out with light oil at an initial oil saturation Soi of 45%, produced a low combustion temperature 250 C. In order to eliminate the probability that low oil saturation may responsible, a run was made at Soi was equal to 60%.

The results are shown in Figs 6-25 to 6-28. At an Soi of 60% a higher combustion

temperature of 300 C was achieved during the first 15 minutes following ignition, but afterwards nearly the same trend as previously with Soi of 45% was obtained, i.e. a stable front temperature of 250 C. It is concluded that the combustion temperature of this type of light oil is controlled mainly by the nature of oil its self (composition) and not the saturation. Thus, the vapour-liquid equilibrium characteristics determines to what extent light ends are vaporised ahead of the front and what is left behind as heavier components, or residual. For a light oil, the residual components amount will be less than for heavy oil, and therefore, less fuel is available to achieve a high temperature.

6.9.5 Effect of sand grain size.

Light oil generally is described by its lack of fuel(coke),or heavy components to sustain in-situ combustion. However, to investigate the effect of using a fine sand, Run 8 was repeated using a sand which has porosity of 45% and permeability of 616 md. compared with the base Run-8 using a course sand with 36% porosity and 1004 md permeability . The results are shown in Figs (6-29) to (6-32). With the fine sand the peak temperature achieved was 260 C over 550 minutes, while in the base case, it was 250 C over 400 minutes. Therefore the fine sand provided more fuel, sustaining a higher peak temperature over a longer period, but the CO_2 and CO trends were not noticeably different. Of course, the higher porosity of fine sand means more oil is available in specific pores compared with the course sand, and the lower permeability means less displacement effect. All of these factors together may contribute fuel enhancement.

6. 9. 6 Effect of tube length

The effect of combustion tube length was investigated to determine whether the results provided by the normal tube are sufficiently accurate for validating the simulation model. The new tube length chosen was 700 cm. Fig 6.33 illustrates the main results obtained compared with the normal tube (125cm).

The simulation temperature is almost the same in both cases, while the oil and water production rate is somewhat higher in the case of long tube, suggesting that experimental tube relatively short length may give a more pessimistic value of recovery. However, recovery is best determined from scaled 3D tests.

The main conclusion is that, the normal tube length of 125 cm is sufficient to simulate a real combustion experiment.

6. 9. 7. Relative permeability

As it was mentioned earlier, the first step in the validation, was to find suitable relative permeability data. Results indicate that a simulation history match with the laboratory results can be obtained when the relative permeability data are modified. Different relative permeabilities sets were used and to keep the number of adjustable parameters to minimum, only relatives permeability were varied during the history matching procedure. Figs 6.34 to 6.36 show the relative permeability data used and the simulation results of production and peak temperature profiles.

Simulation cases 1, 2 in Figs 6.34 and 6.35 show that, with higher relative permeabilities compared to the base case, the production is accelerated, causing a fast depletion of the oil saturation. This leads to lower combustion temperature. Case 3, in Fig 6.36 produce a stable process response and reasonable history matched to the experimental results. This relative permeability data set was in fact selected for use in the simulation studies. It can be concluded therefore, that the process is very dependent on the relative permeability values, since a higher relative permeability means higher accelerated production rate. The increase in the oil mobility due to increased thermal effect means that the amount of oil available for the cracking and the burning reactions and consequently the average peak temperature and the combustion time are significantly reduced.

6 - 10 - Simulation Conclusion

1 . The STARS thermal simulator showed a good capability to simulate the different aspects of the in-situ combustion process.

2. A reasonably effective history match of the experimental results was achieved mainly in terms of the combustion peak temperature. Simulation was less good in predicting the combustion front velocity and the steam zone temperature ahead of the combustion front.

3. The oil and water production profiles were found to be very dependant on the relative permeability values and the time of gas breakthrough into the production well. Specific permeability data and adjustment of production time are needed to obtain complete history matching .

4. Simulation represents an integrated part of the experimental study. It was used to remove some uncertainty in interpreting the experiments results and to investigate internal states (oil, water and gas saturation in the sandpack) of the combustion process, which were not studied during the experiment.

5. The simulation of light oil combustion used in this study has shown that the process is restricted to one of low temperature oxidation reactions, since the average peak temperature achieved was less than 300 C. This attributed mainly to the lack of fuel availability with the light oil.

6. Since a high temperature combustion mode could not be achieved with the light oil, the process is considered to be controlled by LTO. Oil recovery was nevertheless very high (90%OOIP) and therefore, there is great potential for using LTO as major light oil recovery process in high pressure reservoirs.

7. The simulation results were found to be particular sensitive to the oil relative permeability. Thus increasing the permeability resulted in faster production rates, and lower combustion temperature. The simulation was also found to be very sensitive to the air flux. Increasing the flux, increased the front velocity and also production rates. However, it did not affect the combustion temperature in the light oil case due to the limited amount of fuel available.

8. The variation in the number of grid blocks and step time for the simulation mainly affected the computer calculation time and stability, but did not affect the number, or nature of products.

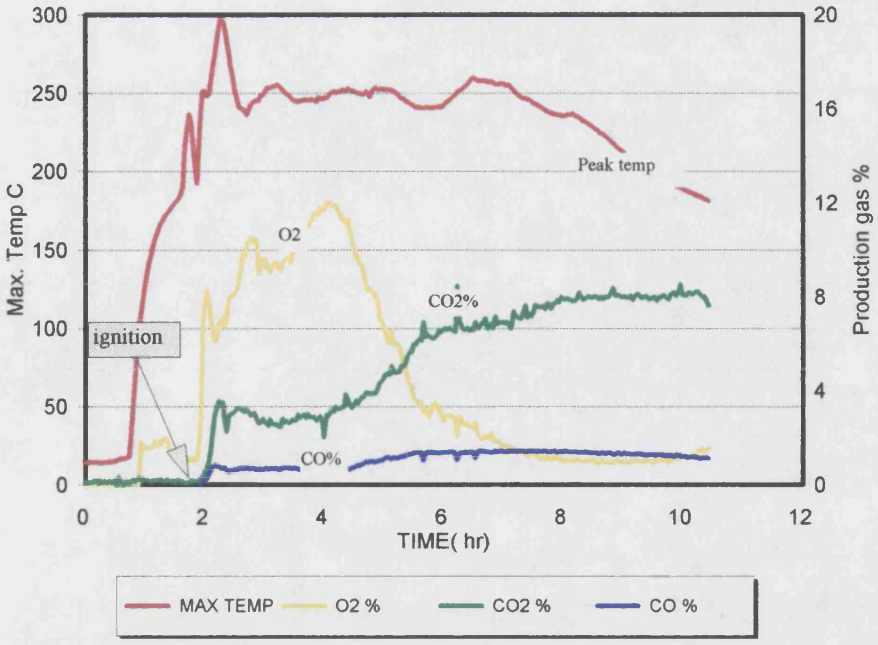


Fig 6.2 Experimental peak temperature and produced gas composition [Run-8, light oil]

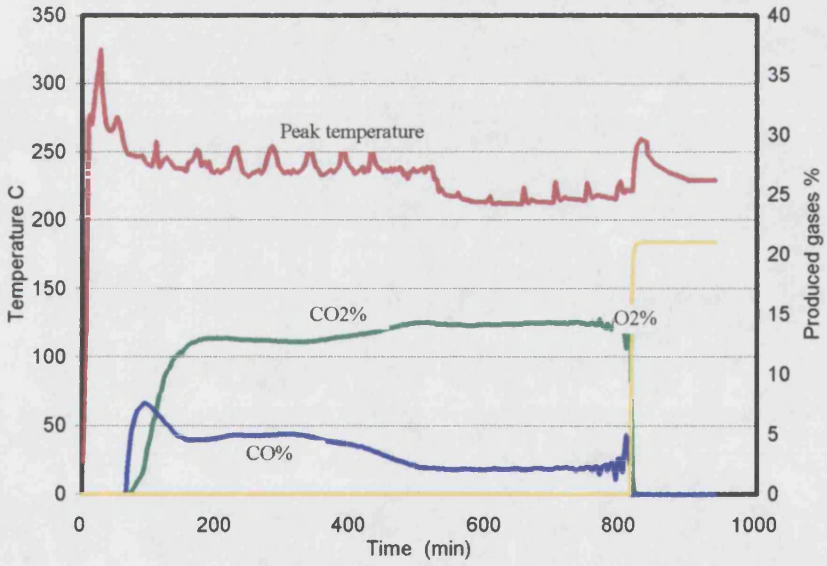


Fig 6.3 Simulatated peak temperature and produced gas composition [Run-8, light oil]

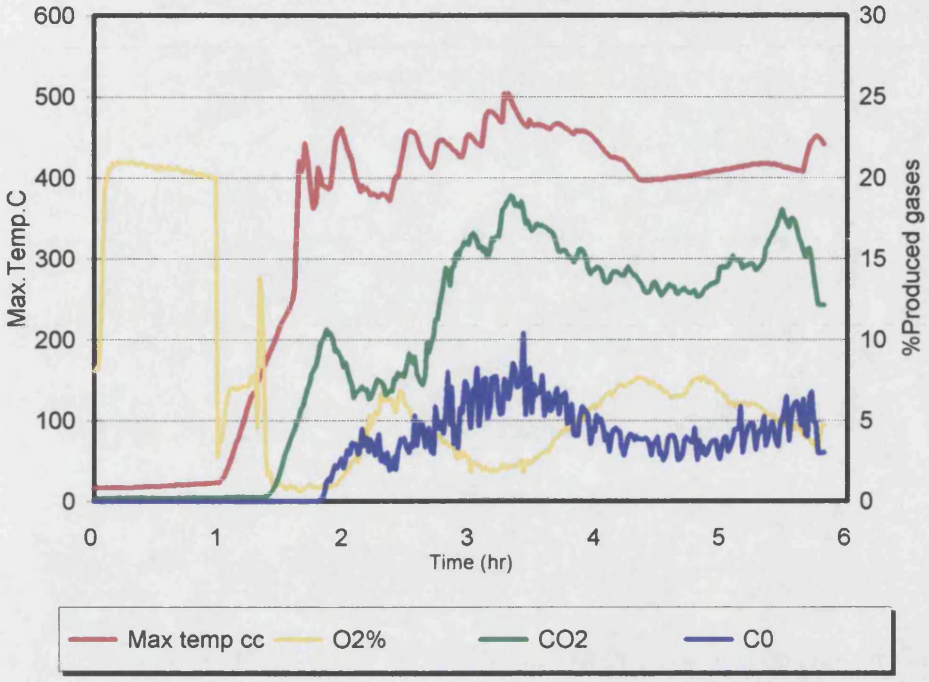


Fig 6.4 Experimental peak temperature and gas composition [Run 6 -medium heavy oil]

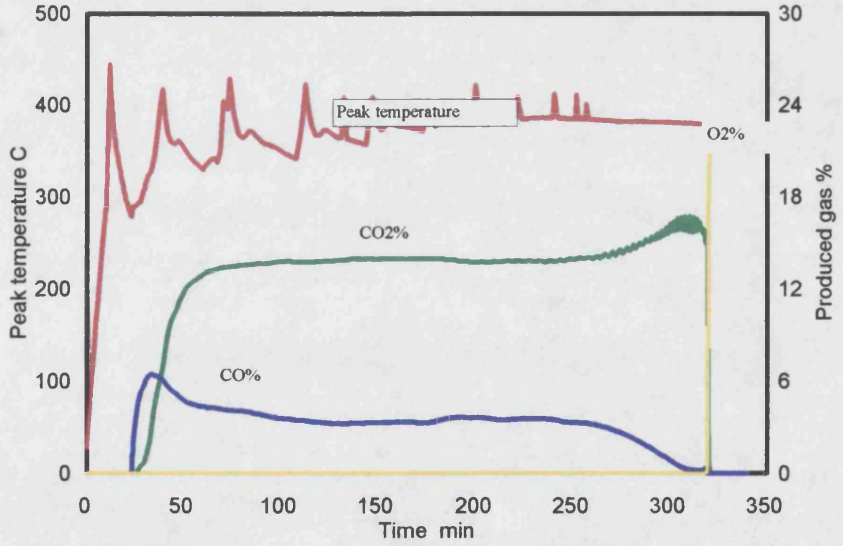


Fig 6.5 Simulatated peak temperature and gas composition [Run 6 -medium heavy oil]

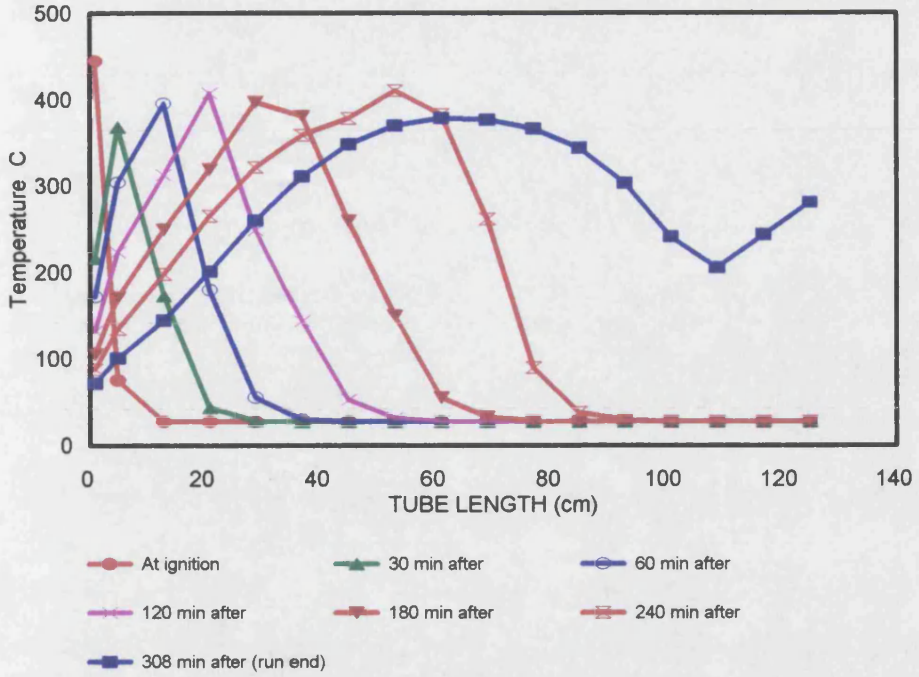


Figure 6.6 Simulation Temperature profile along combustion tube [Run 6 -medium oil]

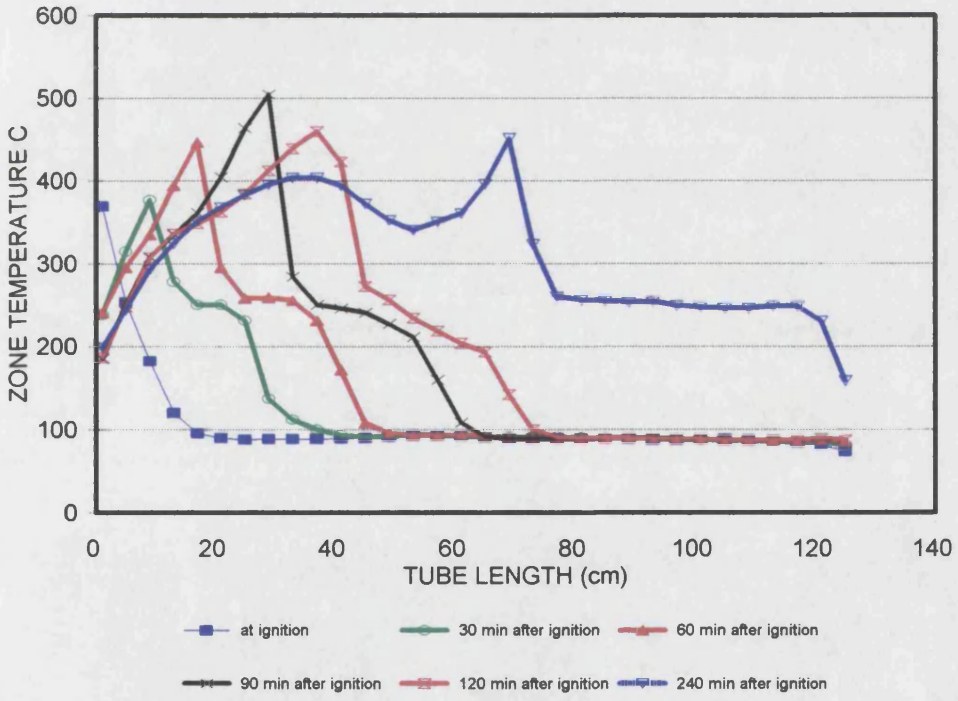


Figure 6.7 Experimental Temperature profile along combustion tube [Run 6 -medium oil]

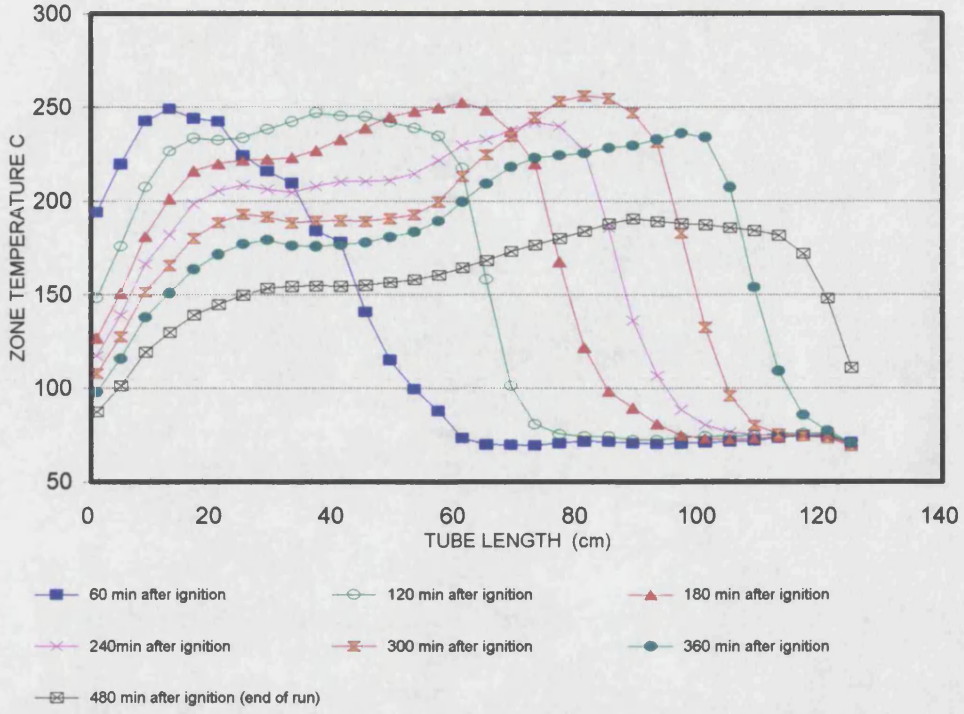


Fig 6.8 Experimental Temperature profile along combustion tube [Run-8, light oil

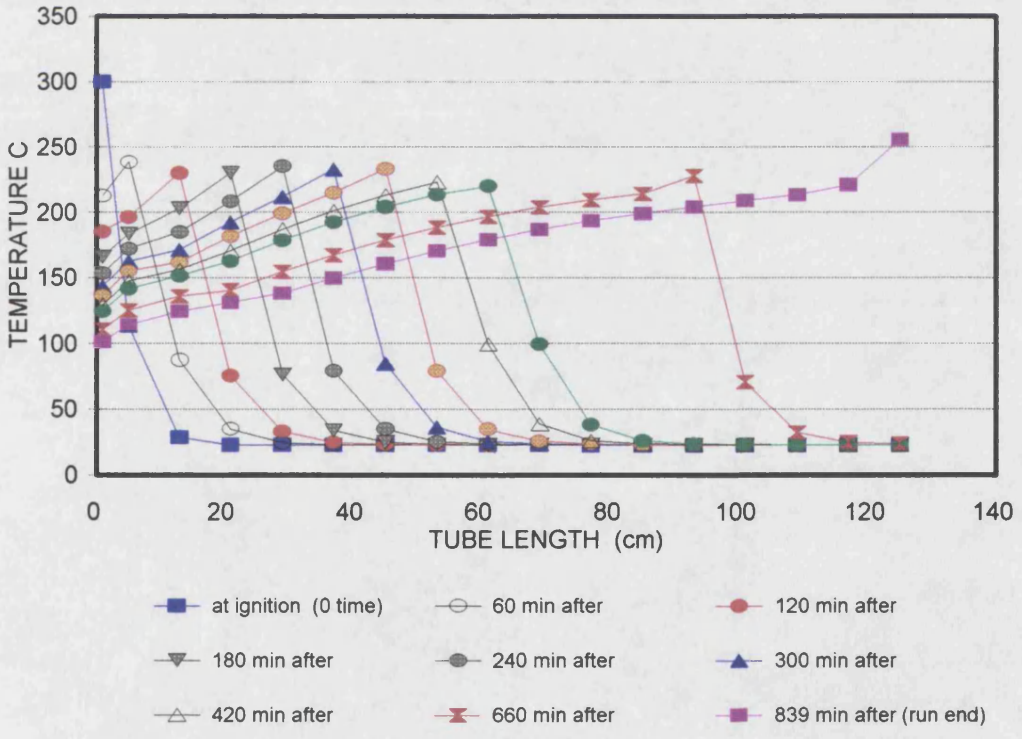


Fig 6.9 Simulated Temperature profile along combustion tube [Run-8, light oil]

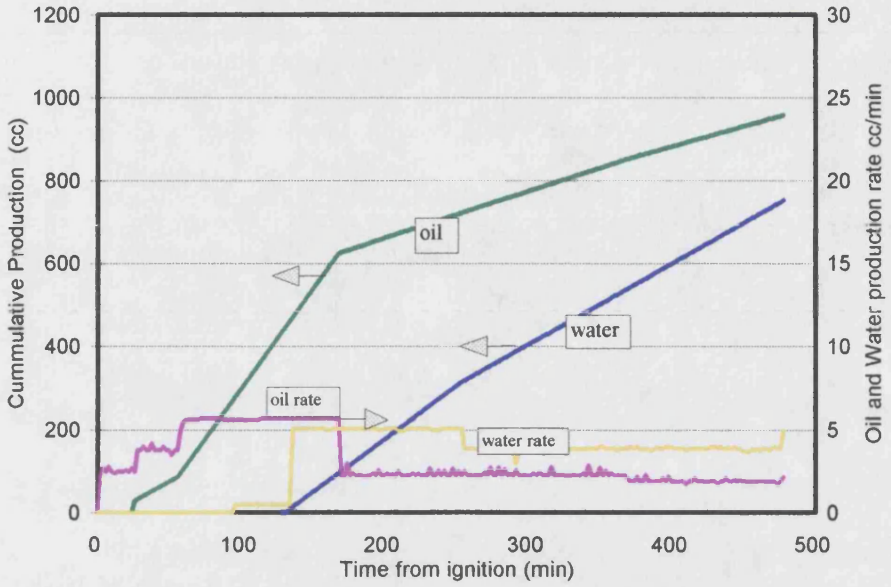


Figure 6.10 Experimental Oil and Water production [Run 8- light oil]

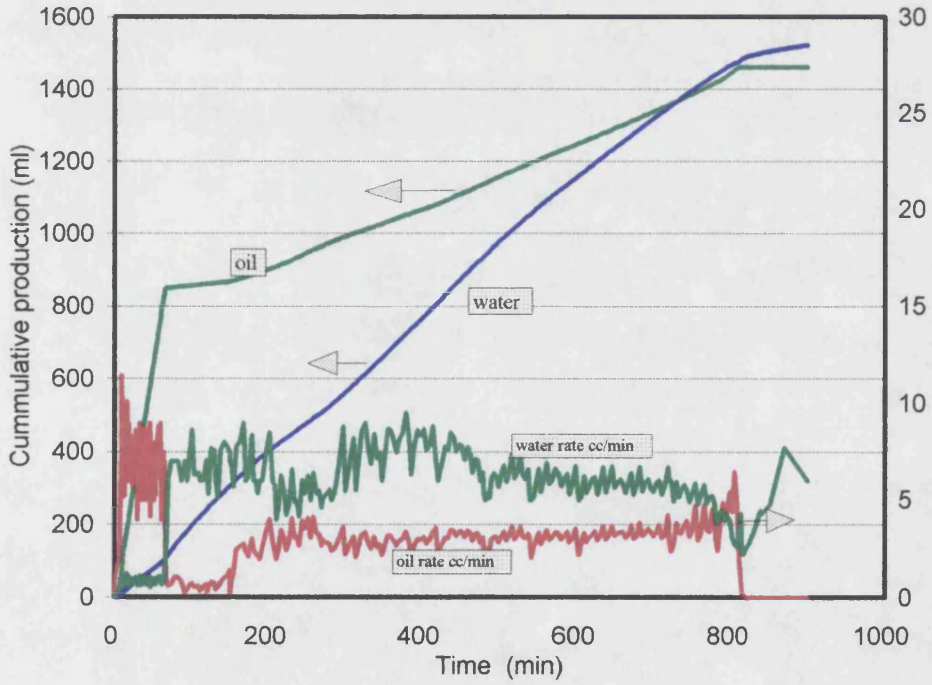


Figure 6.11 Simulated Oil and Water production [Run 8- light oil]

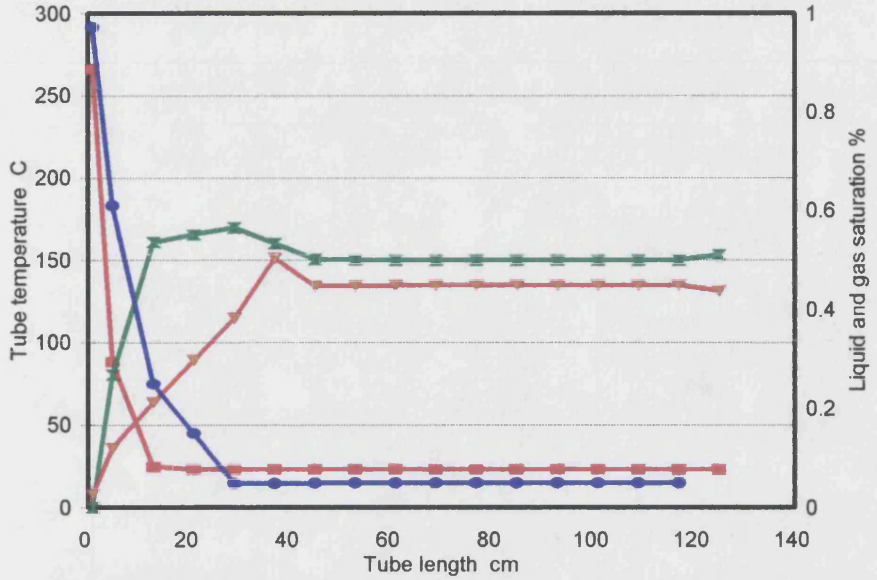


Figure 6.12 Fluid saturation and peak temperature in sandpack (10 min)

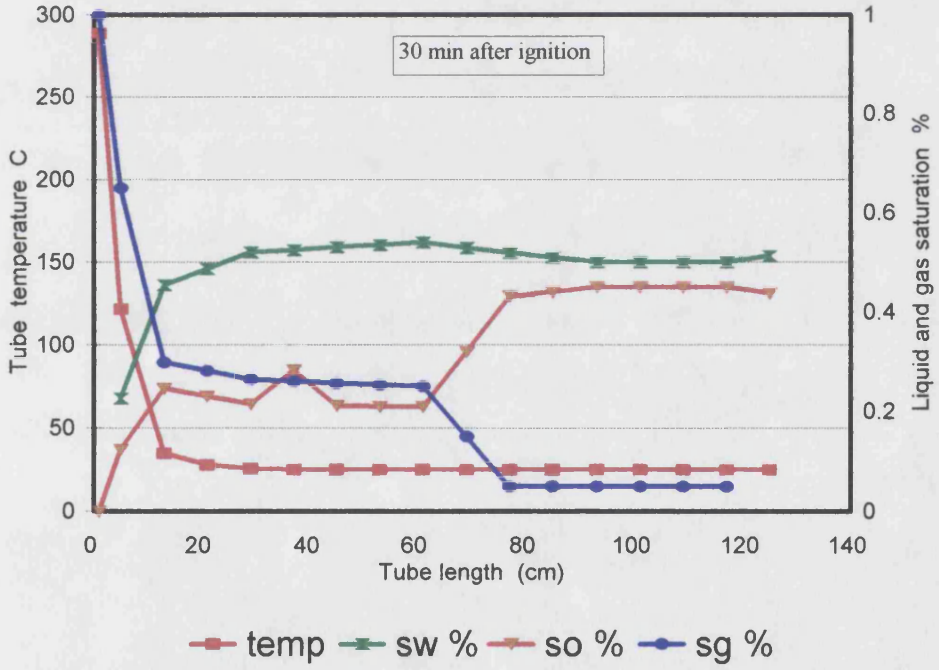


Figure 6.13 Fluid saturation and peak temperature in sandpack (30 min)

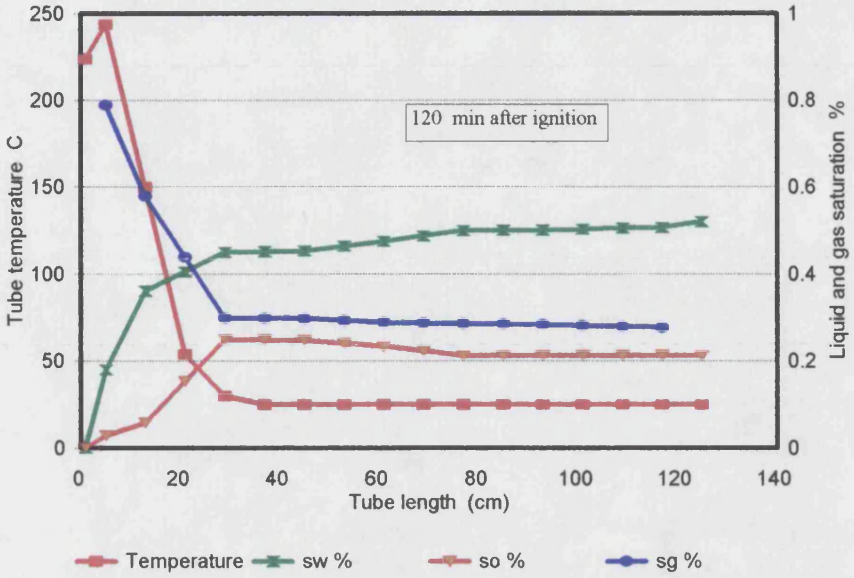


Figure 6.14 Fluid saturation and peak temperature in sandpack (120 min)

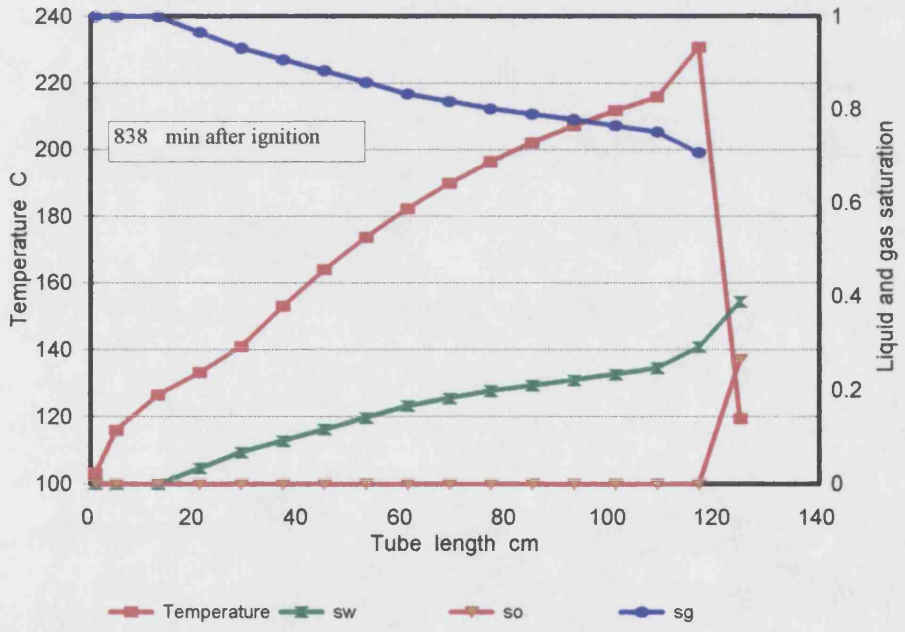
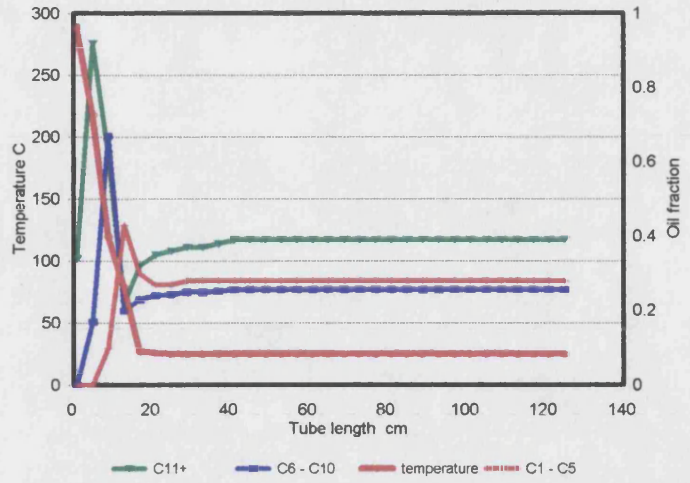


Figure 6.15 Fluid saturation and peak temperature in sandpack (836 min)



Figures 6.16 Pesudo component fraction distribution along the tube (30 min)

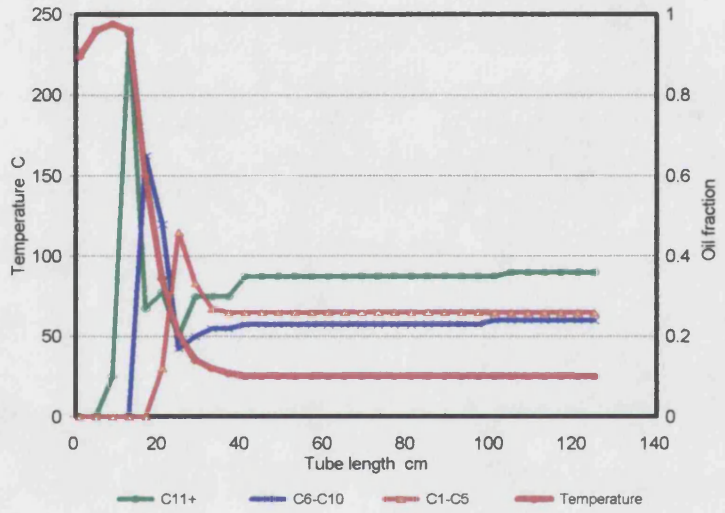


Figure 6.17 Pseudo component fraction distribution along the tube (120 min)

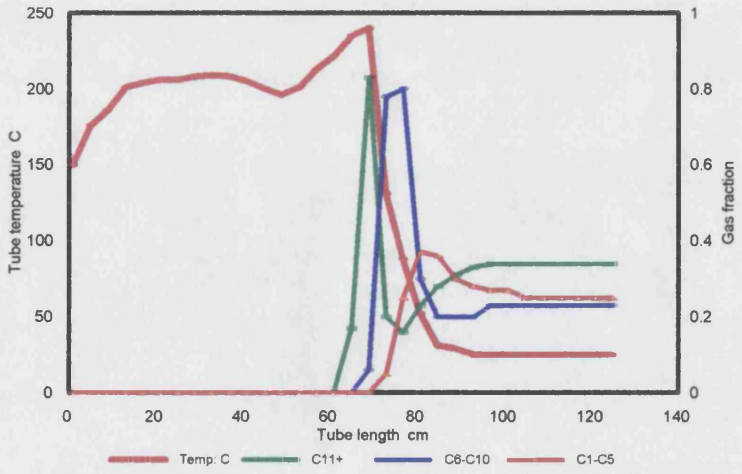


Figure 6.18 Pseudo component fraction distribution along the tube (480 min)

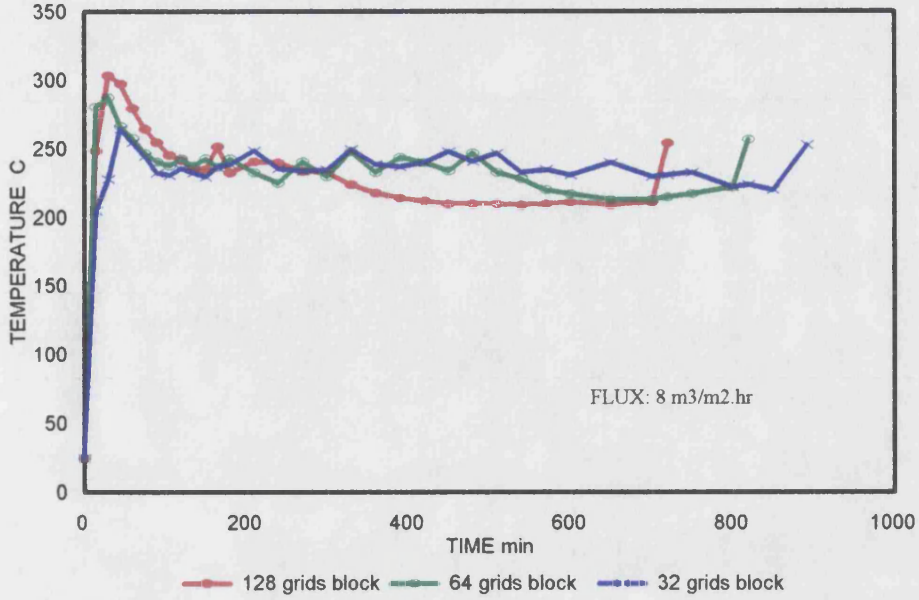


Fig 6.19 Effect of Number of grid blocks on combustion peak temperatu

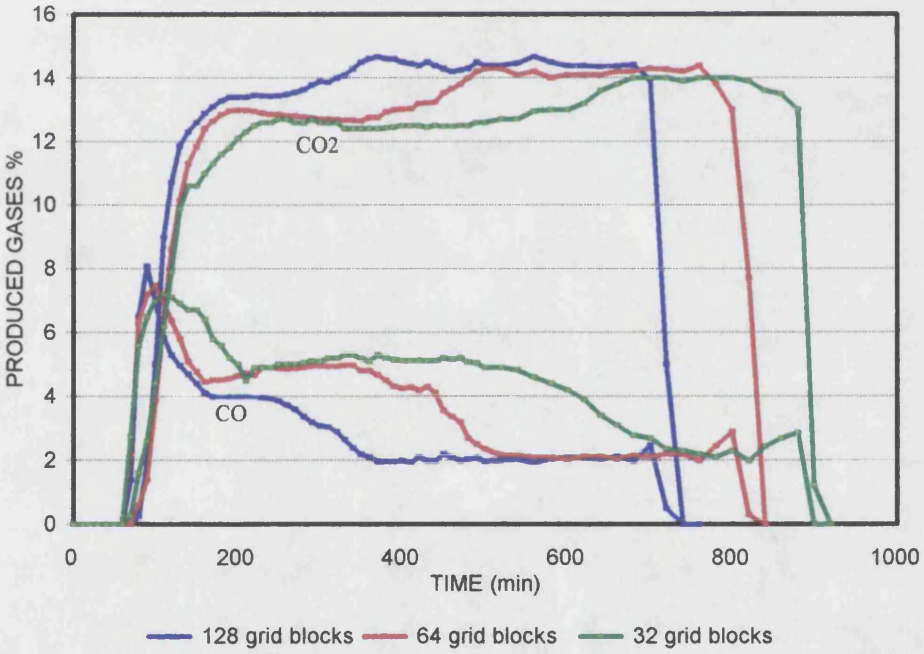


Fig 6.20 Effect of Number of grid blocks on produced CO2 and CO versus combustion time

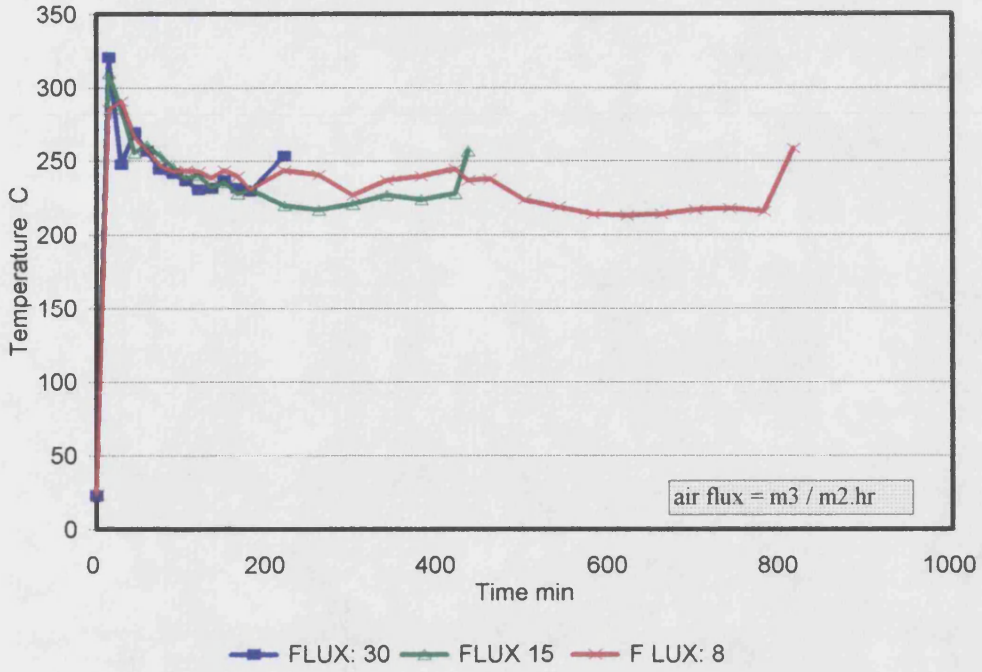


Fig 6.21 Effect of air flux on combustion peak temperature

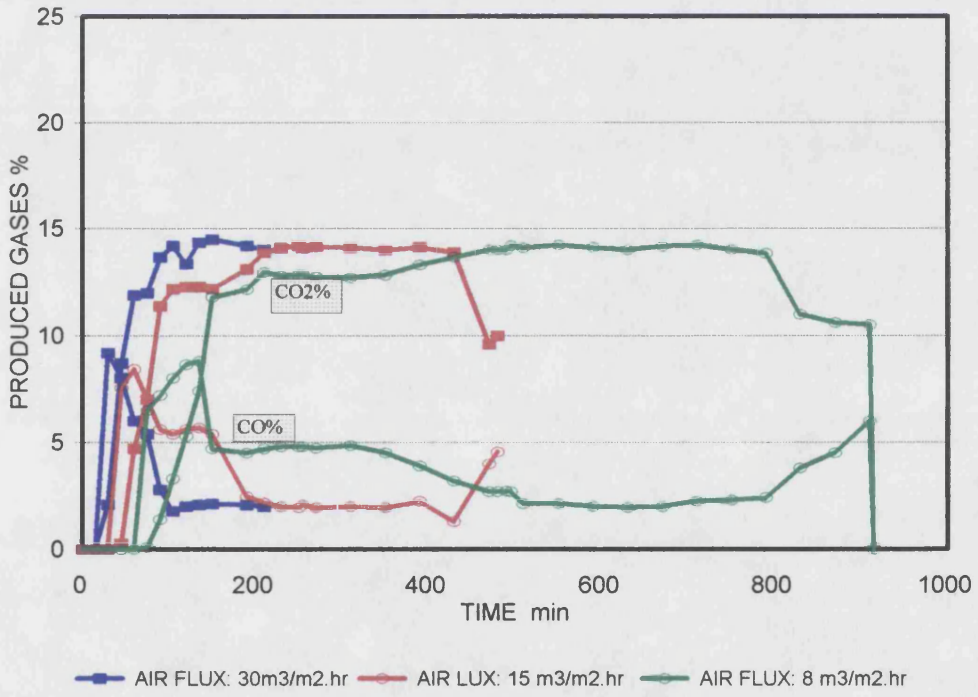


Fig 6.22 Effect of air flux on Produced CO2 and CO

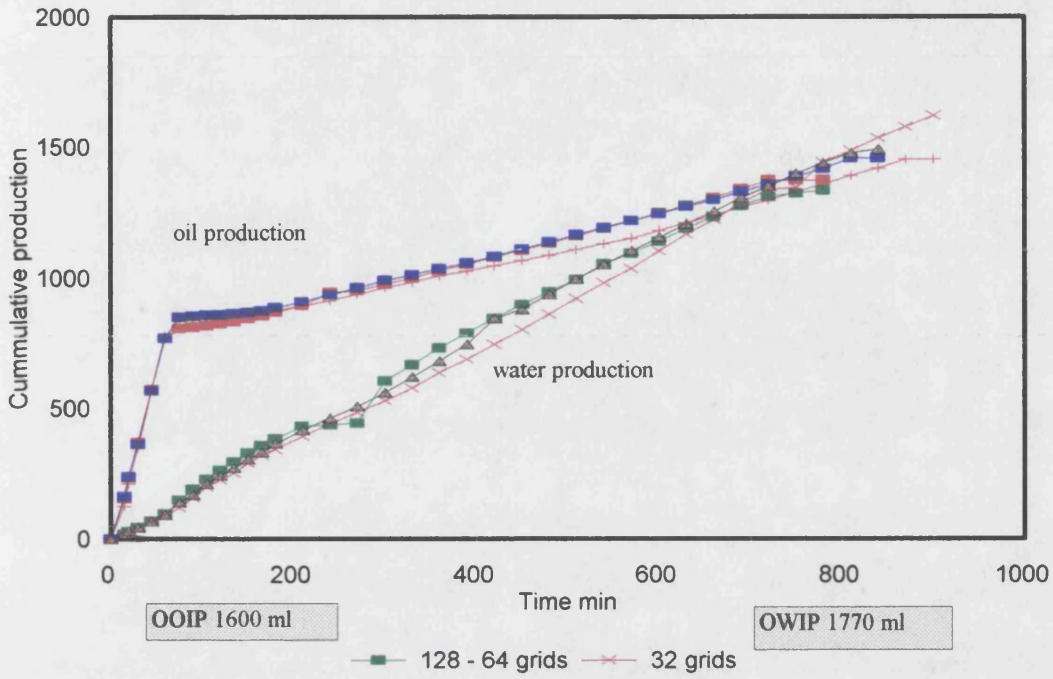


Fig 6.23 Effect of Number of grid blocks on oil and water cummulative productio

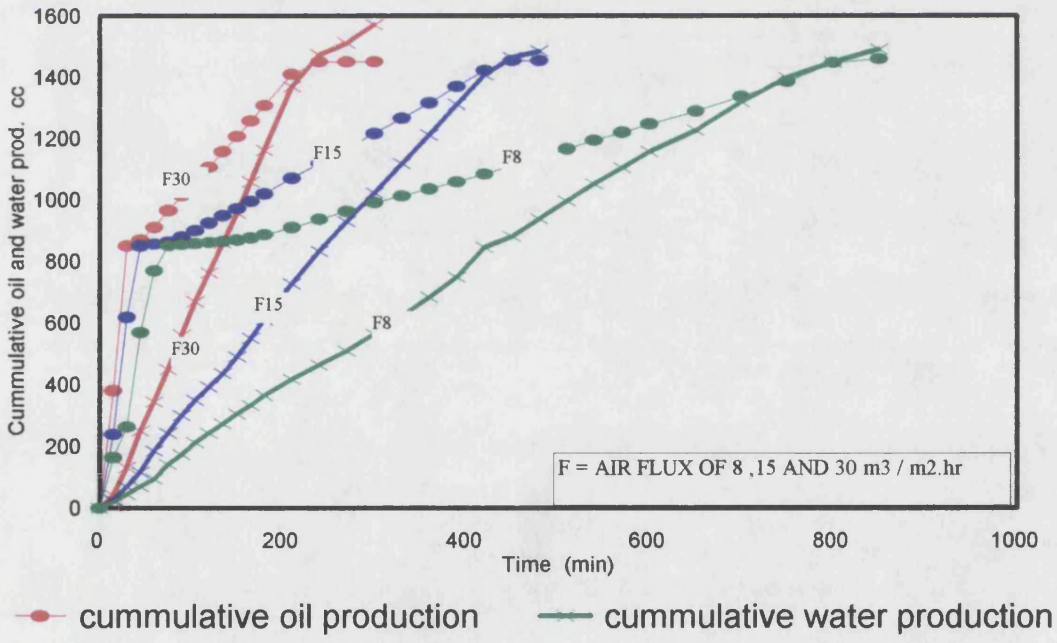


Fig 6.24 Effect of air flux on oil and water cummulative production

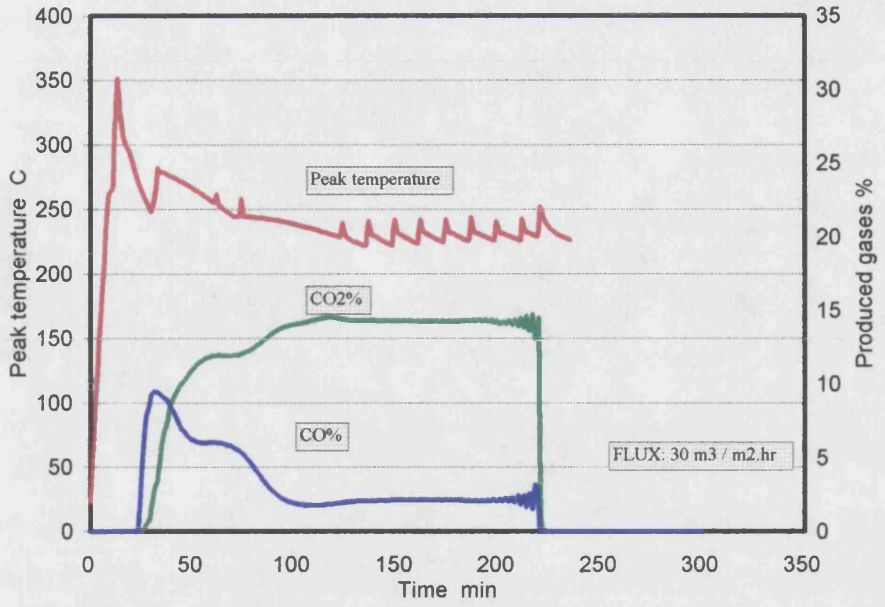


Fig 6. 25 Effect of initial oil saturation on combustion peak temperature and production of CO2 and CO [Soi 45%, Swi 50%]

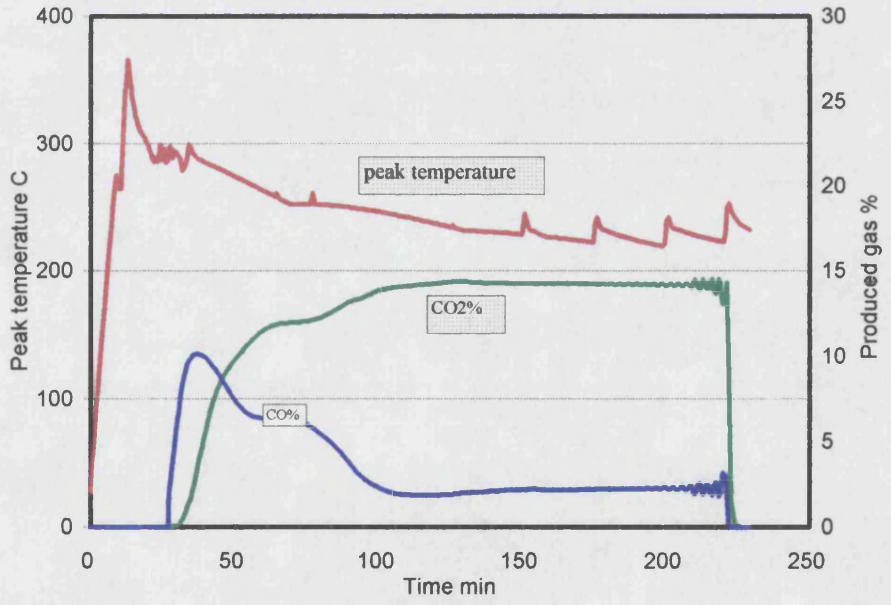


Fig 6. 26 Effect of initial oil saturation on combustion peak temperature and production of CO2 and CO [Soi 60%, Swi 35%]

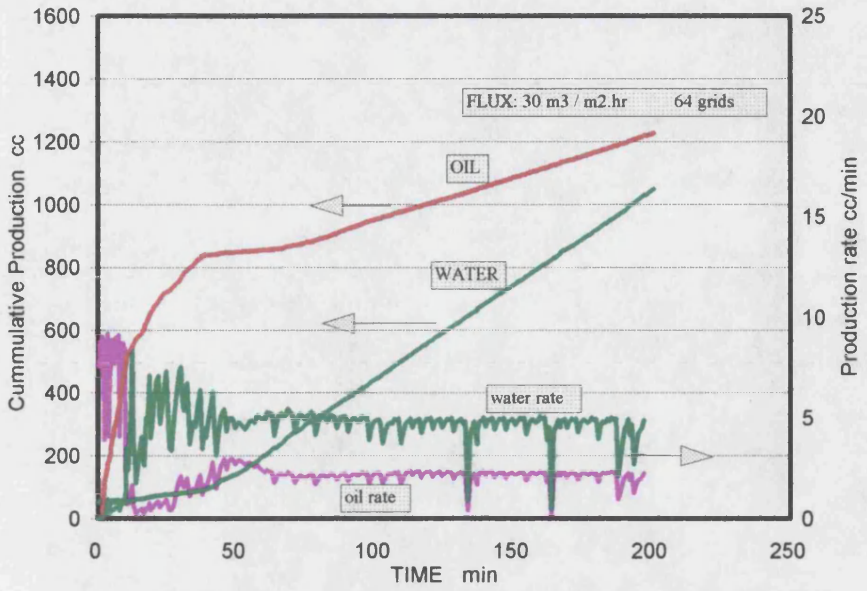


Fig 6. 27 Effect of initial oil saturation on oil and water production [Soi 45%, Swi 50%]

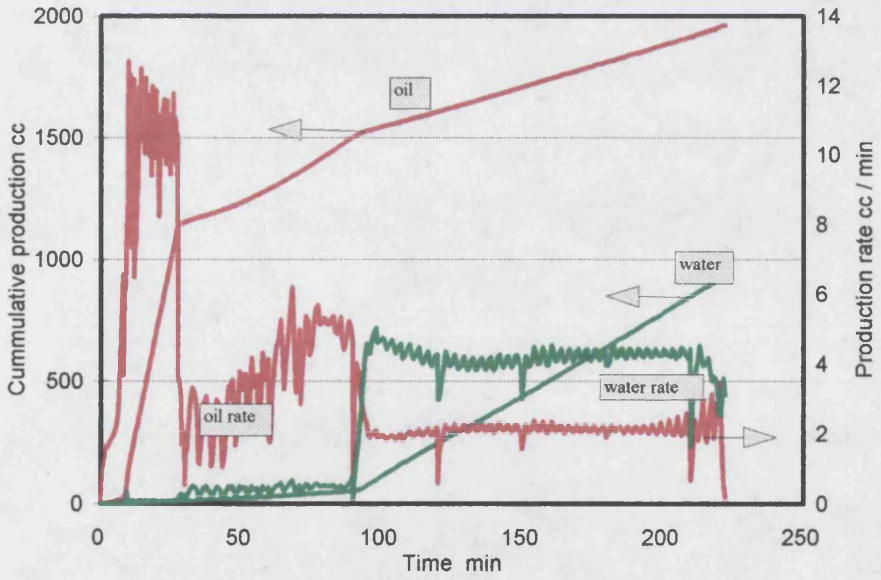


Fig 6. 28 Effect of initial oil saturation on oil and water production [Soi 60%, Swi 35%]

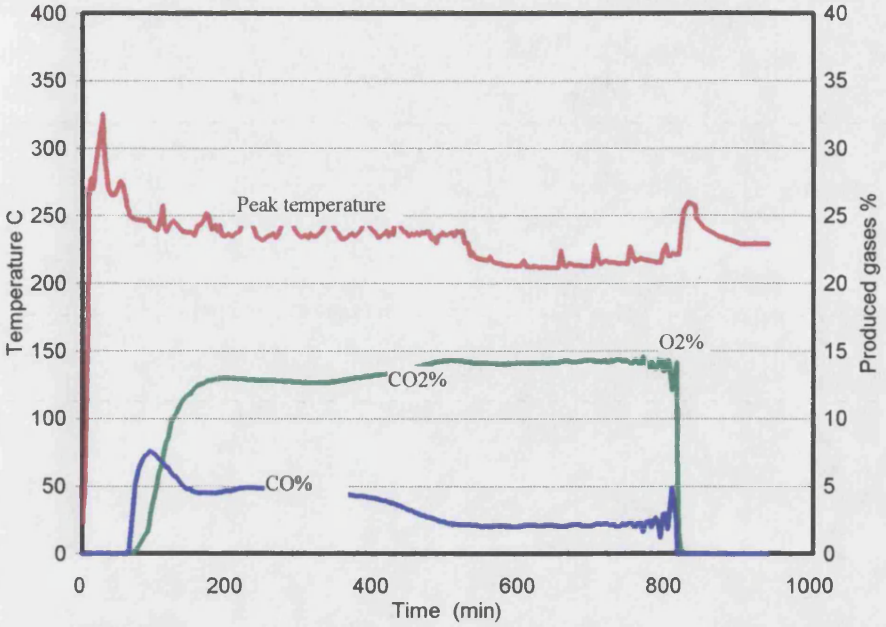


Fig 6.29 Effect of sand type on combustion peak temperature and CO2 and CO produced[W50 coarse sand]

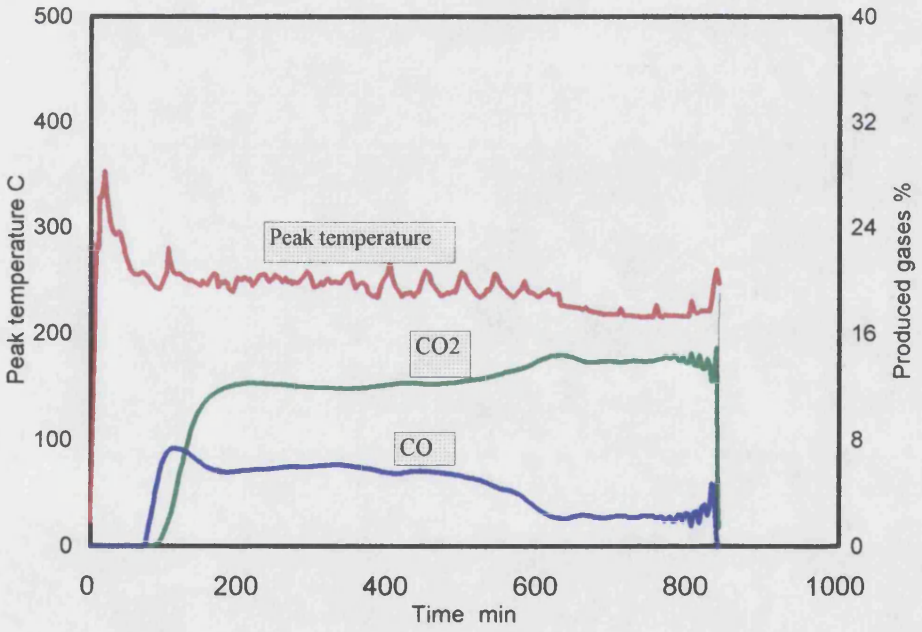


Fig 6.30 Effect of sand type on combustion peak temperature and CO2 and CO produced[W150 fine sand]

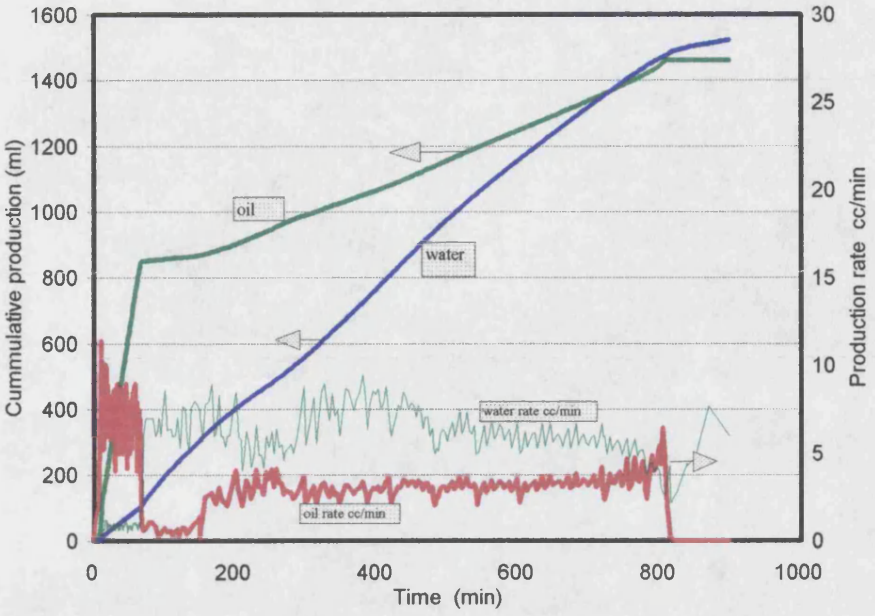


Fig 6.31 Effect of sand type on oil and water production
[W50 coarse sand]

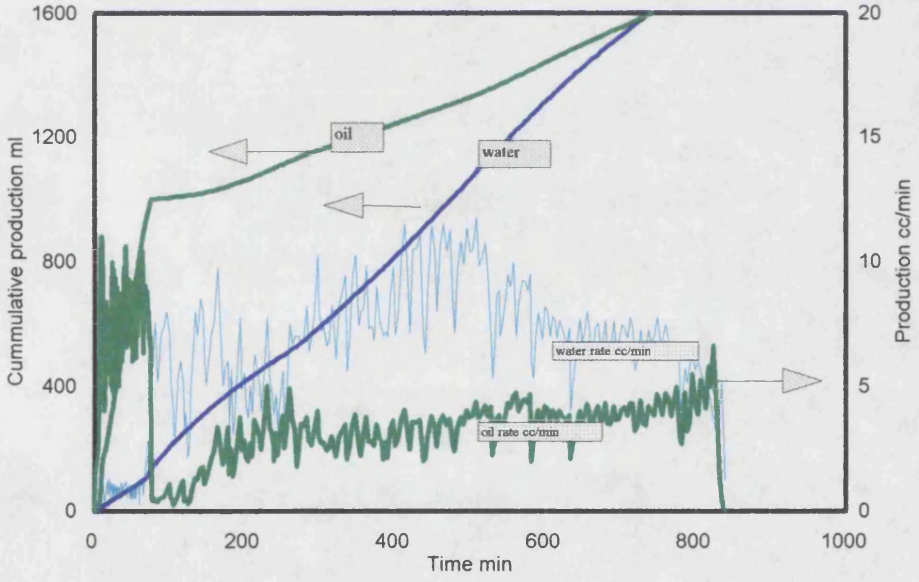


Fig 6.32 Effect of sand type on oil and water production
[W150 fine sand]

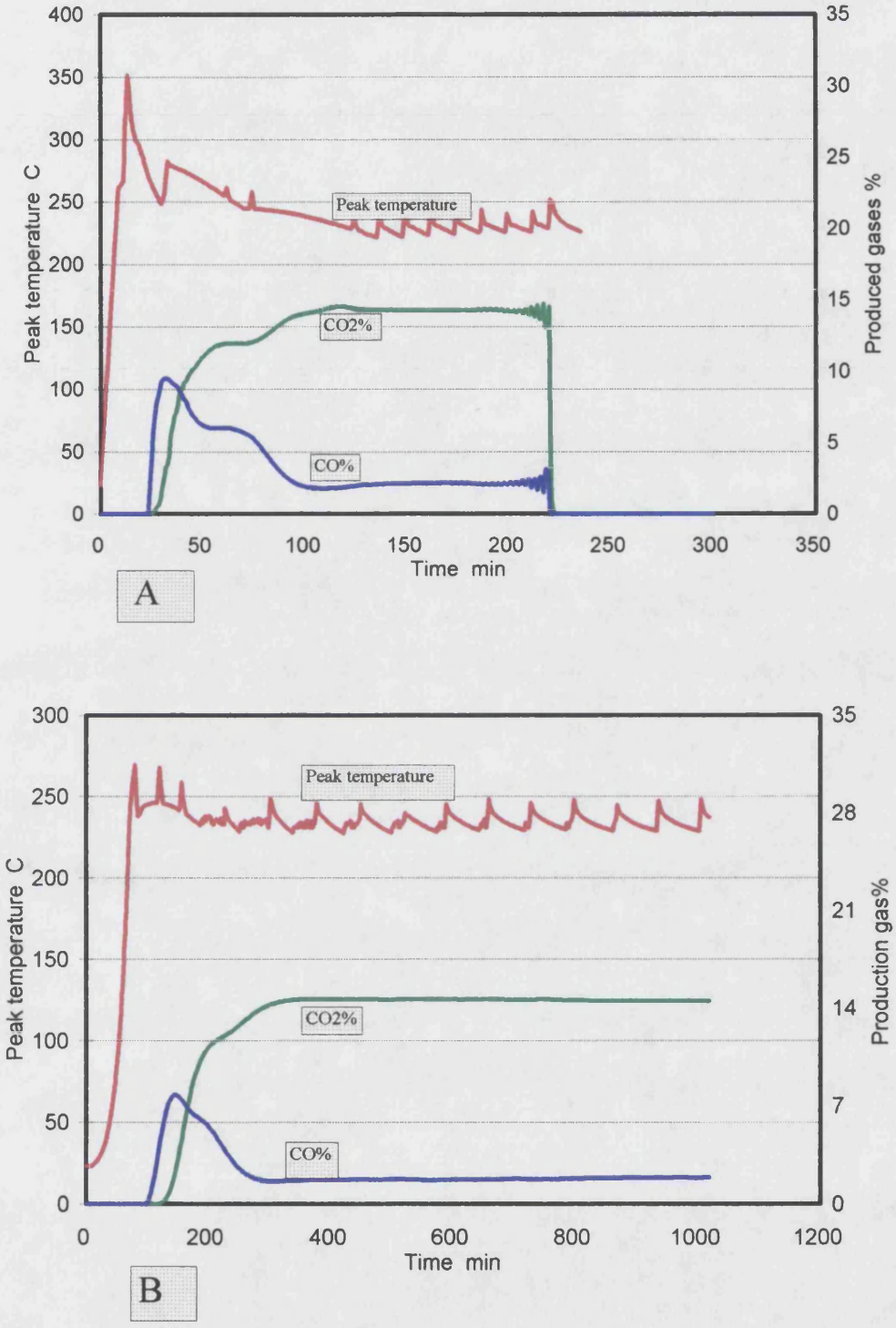
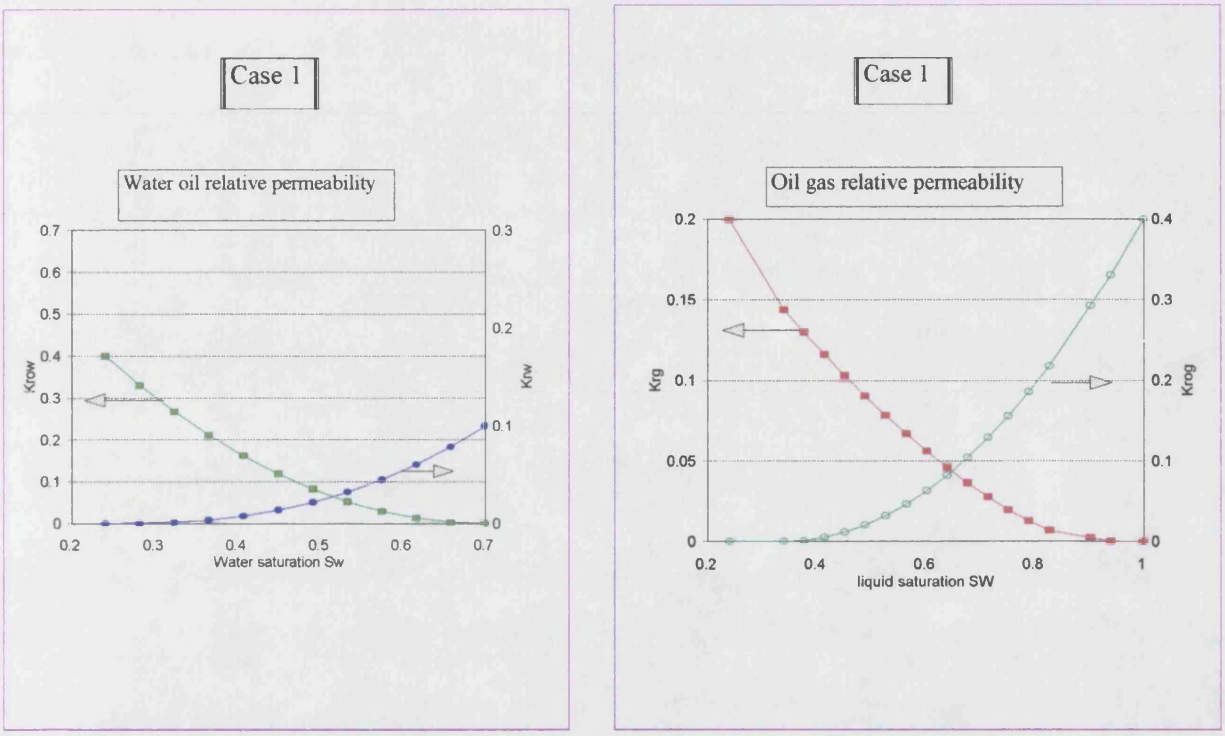


Fig 6.33 Effect of Tube length on peak temperature and produced CO2 and CO
A: normal / experimental tube 1.25 m
B: Simulated tube case 7 m
[Both cases air flux: 30 m3/m2hr, Soi 45% and Swi 50%]



Relative permeability data Source (STARS Application Manual (1996) for light oil)

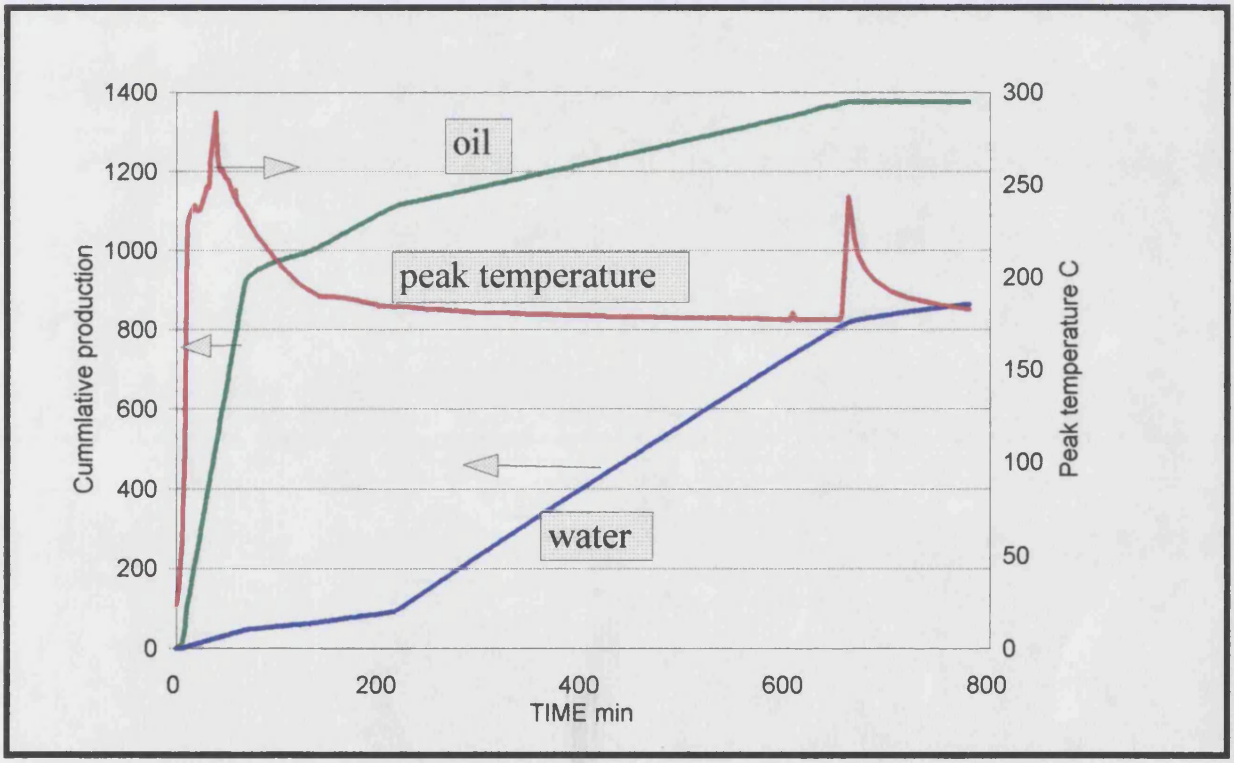
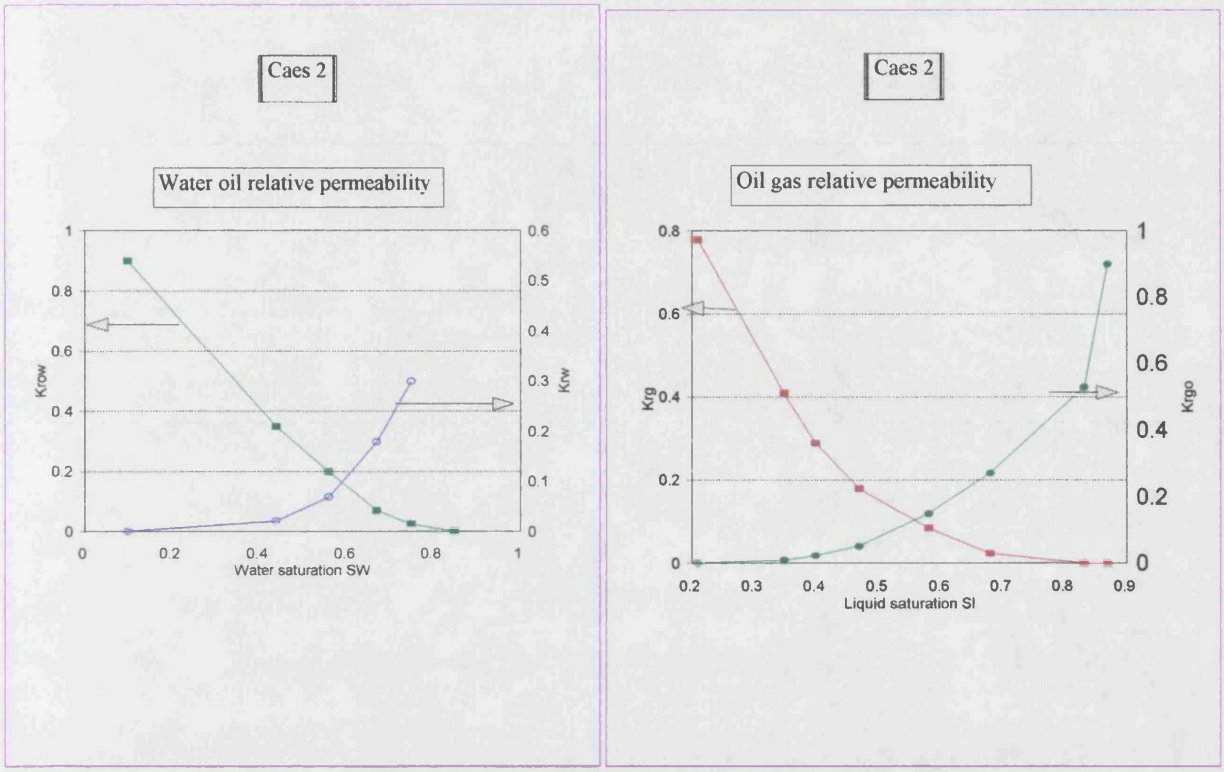


Fig 6.34 Predicted combustion peak temperature and oil and water production using relative permeability data Case 1



Relative permeability data Source (Ben Rahil 1994)

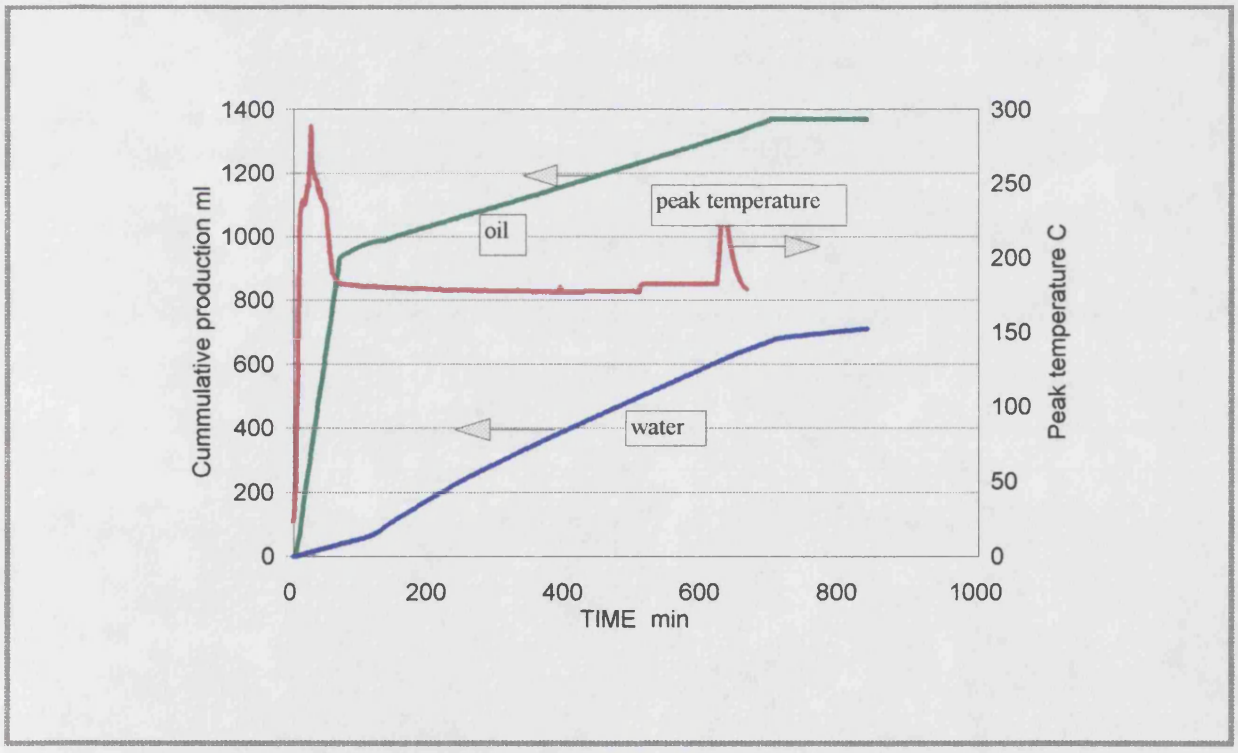
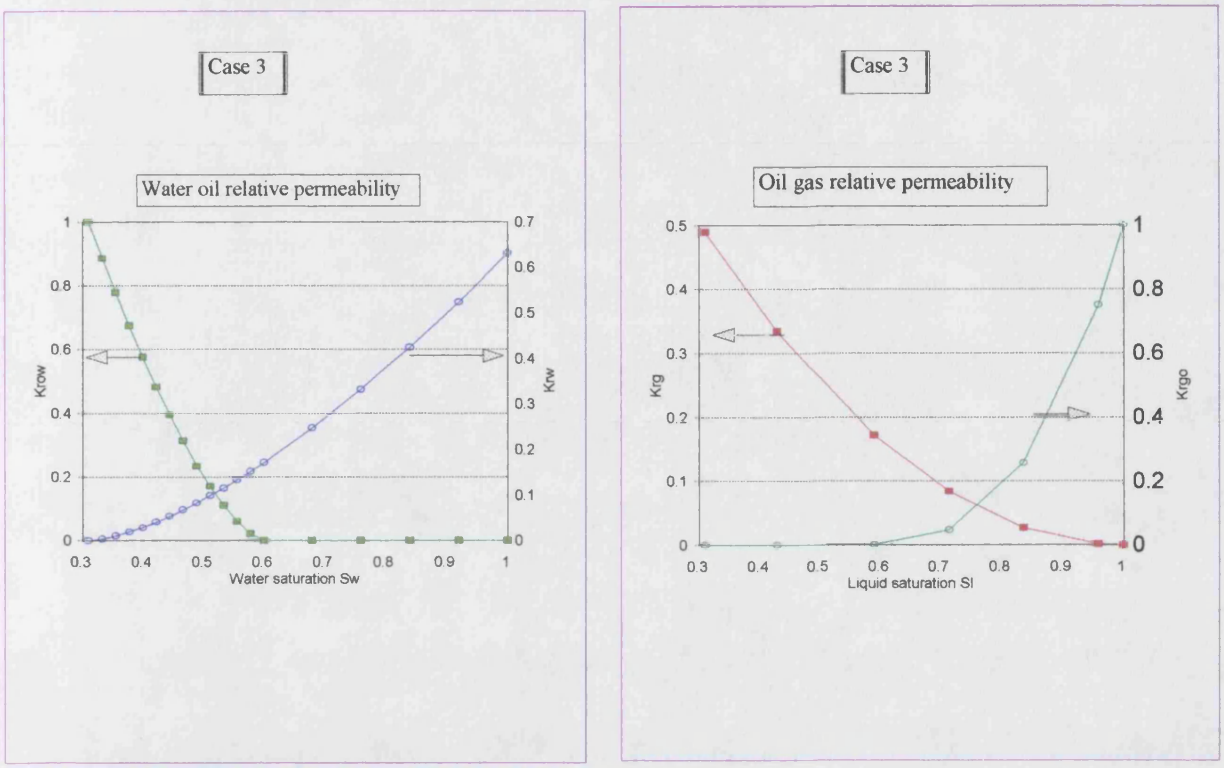


Fig 6.35 Predicted combustion peak temperature and oil and water production using relative permeability data Case 2



Relative permeability data Source (Sakthikumar 1995)

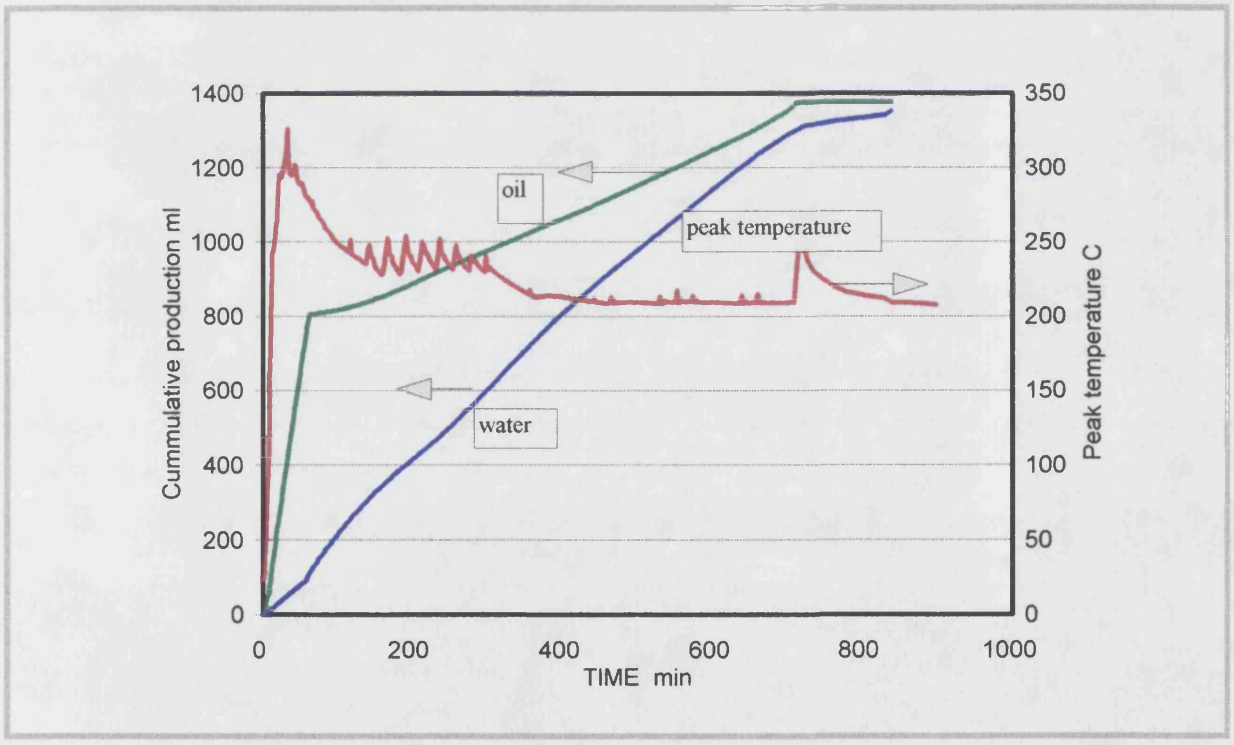


Fig 6.36 Predicted combustion peak temperature and oil and water production using relative permeability data Case 3

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Appendixes

Appendix A

Calculation of oil, water, and sand requirements.

The bulk volume of ISC tube, $Vb = \pi r^2 L$

Where: L = *tube length* = 1.25 *m*

r = *radius of ISC tube* = 0.05 *m*

$Vb = 0.009821\ m^3 = 9821\ cc$

The pore volume $Vp = Vb * \varnothing$

$\varnothing$ *is the porosity. The porosity depends on the type of the sand used and the amount of clay or cement added.*

Tables (A - 1) to (A - 3) illustrate the physical properties such as porosity, permeability and matrix surface area of the different type of sands used in this study.

Run -3, Run -4, Run -6.

These runs were conducted using coarse sand, W50 with 10% added clay

The porosity (W50 - 10% clay) = 36.53 %

The pore volume $Vp = Vb * \varnothing$

$= 9821.4 * 36.53$

$= 3587.8\ cc$

So = *Oil saturation* Sw = *Water saturation* Sg = *Gas saturation*

Vo = *Volume of oil* Vw = *Volume of water* Vg = *Volume of gas*

$So = 60\ \%$ $Sw = 35\ \%$ $Sg = 5\ \%$

$Vo = Vp * So = 3587.8 * 0.6 = 2153\ cc = 2.15\ L$

$Vw = Vp * Sw = 3587.8 * 0.35 = 1256cc = 1.26\ L$

$Vg = Vp * Sg = 3587.8 * 0.05 = 179\ cc = 0.179$

Vs = *volume of sand* $= Vb - Vp = 9821.4 - 3587.8 = 6233.6\ cc$

Weight of sand mixture $= Vs$ * *sand density (g/cc)*

$= 6233.6 * 2.534 / 1000 = 15.8\ kg$

*90 % sand = 15.8 * 0.9 = 14.22 kg*

*10 % clay = 15.8 * 0.1 = 1.58 kg*

Run - 5:

Sand type : fine sand W-150

Porosity ∅ = 45.5 %

Pore volume = 4470 cc

So = 47.7 Sw = 28 Sg = 24.3

Volume of oil = 2120 cc

Volume of water = 1240 cc

Volume of gas = 1110 cc

Volume of sand mixture = 5351.4 cc

Weight of sand mixture = 13.662 kg

90 % sand = 12.3 kg

10 % clay = 1.3662 kg

Run - 7 and Run -8:

Coarse sand W50, with 10% clay

Porosity = 36.53 %

Pore volume = 3587.8 cc

So = 45 % Sw = 50% Sg = 5 %

Vo = 1615 cc

Vw = 1794 cc

Vg = 179 cc

Vs (volume of sand mixture) = 6233.6 cc

Sand density = 2.534 g/ cc

Weight of sand mixture = 15.8 kg

90 % sand = 14.22 kg

10 % clay = 1.58 kg

Physical properties of reservoir materials Table (A - 1):

	average particle diameter(μm)	specific surface area (m^2/kg)
coarse sand (W50)	300 *	14.9
fine sand (W150)	125 *	48.3
clay **	0 - 1	16000
cement ***	17.5	1000 -estimated-

- Specific surface area measured by Castings Development centre, Birmingham.
- * Particle diameters supplied by Buckland Sand and Silica Co.Ltd, Surrey.
- ** Data supplied by ECC International, St. Austell, Cornwall.
- *** Data supplied by Castel Cement Ltd., Birmingham.

Physical properties of reservoir materials Table (A - 2):

Sand type	Clay content (wt %)	Matrix surface area m2/kg
100 % W50	0	14.9
97 % W50	3	494
95 % W50	5	814
90 % W50	10	1613
100 % W150	0	48.3
90 % W150	10	164.3

Physical properties of reservoir materials Table (A- 3):

Sand type	Clay content (wt. %)	Grain volume (cc)	Grain density(g/cc)	Porosity (%)	Gas Permes(mD)
100 % W50	0	58.53	2.507	39.05	1503
97 % W50	3	59.62	2.522	38.53	1042
95 % W50	5	61.54	2.534	38.11	1049
90 % W50	10	61.16	2.546	36.53	1004
100% W150	0	51.23	2.515	45.51	674
90 % W150	10	52.96	2.553	42.52	616

All data in Table (A -3), were measured by AEA Technology, Winfrith.

Appendix B

Material balance calculation

Example for run - 6:

The calculation was done on the basic assumption, that O_2 consumed at temperature above 300°C where carbon oxides and water the main reaction products following this stoichiometric equation:

$CH_X + (1\text{-}r/2 + X/2)\ O_2 \longrightarrow (1\text{-}r)\ CO_2 + rCO + X/2\ H_2O$ (Burger 1985)

Where :- $r = CO / (CO+CO2)$

$X =$ H/C (Atomic hydrogen to carbon ratio for the fuel)

As the O_2 is injected only when the temperature is around 300°C , thus no low temperature oxidation (LTO) is considered.

	Density (kg/m^3)	RMM (Kg/kmol)
CO2	1.9768	44
CO	1.2501	28
O2	1.4289	32
N2	1.2507	28

Experiment air flux = 60 m^3 / m^2.hr

Air injection period = 4.52 hr

Tube cross section area = 0.00785 m^3

Total injected air = 60 * 4.52 * 1000 * 0.00785 = 2129 l (Litre)

N_2 Injected = 2129 * 0.79 = 1682 l

O_2 Injected = 2129 * 0.21 = 447 l

Gas produced:-

Total gas produced = 1991L

CO_2 (avg) = 14.75 %

CO (avg) = 4.58%

O_2 (avg) = 4.93

CO_2 prod = 1991 * 0.1475 = 393.76 L

CO prod = 1991 * 0.0458 = 91.18 L

O_2 prod = 1991 * 0.493 = 98.5 L

Hydrocarbon(light oils) in the production gases were measured using the Gas Chromatograph and were found to be in very small quantities, there for they will be ignored in this calculation.

Assume the reminder of the gas to be N_2

N_2 produced = 1991- (393.76 +91.18+98.5) = 1508 L

Mass calculation

Injected gas:

N2 (inj) = (1682 /1000) * 1.2507 = 2.104 kg

O2 (inj) = (447/1000) * 1.4289 = 0.63 kg

Produced gas:

CO2 (prod) = (293.76/1000)*1.9767 = 0.58 kg

CO (prod) = (91.18/1000)*1.2501 = 0.114 kg

O_2 (prod) = (98.5/1000)*1.4289 = 0.1407

N_2 (prod) = (1508/1000)*1.2507 = 0.1407kg

Oil and Water calculation:

Oil (in) = (2.54/1000)* 935 = 2.375 kg (*Clair oil density = 935 kg/m3*)

Water (in) = 1.48 kg

Oil (prod) = (1.769/1000)*935 = 1.65 kg

Water (prod) = 0.714 kg

Material left in the tube = Total material in - Material produced

Material left in tube = (2.375+1.5)-(1.65+0.714) = 1.487 kg

assume to be at saturation of 45% for oil and 50% for water

Oil left in tube = 0.669 kg

Water left in tube = 0.744

Overall mass material balance:

INPUT (Material) = OUTPUT (material) + Accumulation

[N2 + O2 + Oil + Water] = [CO2 +CO+N2+O2+Oil +Water] + [Accumulation]

Input = 2.104 + 0.63+2.373+1.48 = 6.589 kg

Output = 058+0.114+1.886+0.1407+1.65+0.714 = 5.0847 kg

Accumulation (material left intube) = 1.487 kg

(assume 25% extra accumulation for gases left in tube, total accumulation =1.737 kg)

i.e Error = [6.589 - (5.0847+1.737)]/(6.589)*100 = 3.

<u>Components mass balance:</u>

Air to fuel requirment:

Volume of gas required (VG sm3/kg) = 56.3*(2- r + x/2)/(12 +x) (Burger 1985)

where r = CO/(CO+CO2) and was at average of 0.27 for overall the combustion period.

X = H / C (hydrogen to corbon atomic ratio and it was astimated at 0.3 at the very stable combustion period)

VG = 56.3 * (2 - 0.27 + 0.3/2)/(12 + 0.3) = 7.23 Sm3 / kg of fuel

O2 to fuel requirment.

$= 7.23 * 0.21 = 1.518\ Sm^3/kg$

Amount of fuel burnt.

= O2 consumed / O2 to fuel requirment

O2 consumed = O2 injected - O2 produced

= (447 - 98.5) = 348.5 L

Amount of fuel burnt = 348.5 / (1.518 * 1000) = 0.23 kg

Oil balance.

Oil Original In Place = 2.375 kg

Oil (prod) = 1.65 kg

Oil left in the tube = 0.669

Oil burnt as fuel = 0.23kg

Error = [oil in - (oil prod + oil left + oil burnt) / oil in] * 100

= 7.3 %

Water balance.

Water in + water produced by reactions = water prod + water left in cell

water produced by reaction = (moles of CO prod/ r)* (X / 2)

= ((0.114/28)/0.27)*(0.3/2)

= 0.0023 Kmol = 0.0023 x 18 = 0.04 kg

water in = 1.48 kg, water prod = 0.714 kg , water left = 0.744, water by reaction 0.04 kg

Error = 4 %

Appendix C *Specifications of the system equipment(Referenced in Fig 6.4*

Item Description	*Purpose and specification*	*Manufacturers*
AAVs (air activated valves) HB series, on/off	AAVs valves are used to route either Oxygen or Nitrogen into the combustion tube and shell. These valves are used also either to deliver or cut off the produced gases or liquid or to isolate any part of the system when it is required. These valves are activated by supplying 80psi compressed air via the solenoid valves (SVs).	Swagelok Co. Bristol valves and fitting Co.Ltd Bristol , UK.
CPCs Current to Pneumatic Converter, Type 101X	They are located to operate the pressure regulators (PPRV1-PPRV4) and the back pressure regulators (PPRV5- PPRV6) and the operating pressure control valve (Palton valve) through 2 way direct acting solenoid valves Svs. These precision instruments are designed to convert electric input signals (4 - 20 mA) into proportional pneumatic output signals (2 - 80 psi)	Waston Smith Ltd. Leeds LS6 2RT UK
PPRVs Precision Pressure Regulators valves, 54-2300 series (normally closed)	PPRV1 - PPRV4 are used to provide a uniform inlet Oxygen or Nitrogen into the combustion tube and shell. PPRV5, PPRV6 are located on vent lines connected to the combustion tube inlet and the pressure shell outlet and they used to terminate the experiment in emergency case. These regulators are actuated with a 100 psig (maximum) air signal through the CPCs.	Tescom Corporation Coatbridg ML5 - 3AG

Item Description	*Purpose and specification*	*Manufacturers*
PRVLs Pressure Reducing Regulator for liquid 44-2300 series, spring loaded	The system contains two PRVLs . PRVL1 is located on liquid discharge line from HPS and used to throttle liquid pressure to less than 30 bar (LPS working pressure). PRVL2 is located on the discharging liquid line from LPS. It is used to reduce the liquid pressure to the atmospheric pressure for samples collecting.	Tescom Corporation
Pts Pressure Transducer Model Super TJE ultra precision gauge	Pressure Transducer Pts, are used to measure the injection gas pressure at N2 and O2 injection lines, top and bottom of tube, shell and along the gas and liquid production system. They are designed to withstand a pressure range of 10 to 3000 psi and operating temperature of -65 to 250F	RDP electronic Ltd, Wolverhamton WV 10 OPY UK
Svs Solenoid valves	These valves are opened when energized to supply compressed air to open normally close air activated valves AAVs. Solenoid valves are operated from 240V, and interfaced to the computer using 2A solid state relays operated from the National Instrument interface card digital output	ASCO, Coppas Control. Ltd Bristol BS15 7DA UK

Item Description	*Purpose and specification*	*Manufacturers*
LMFs Mass flowmeter control Model 5850	The system contains two LMFs . LMF1 is used to set the flow rate of Oxygen into the combustion tube at scale range of 0 to 3 litre / min at 5C operating temperature. LMF2 is utulized to set the nitrogen flow rate into the combustion tube with full scale of 0 to 10 litter/min. They require a power supply of +/- 15 V DC output signal and input set point in the range of 0 to 5V DC. LMFs are needed to be calibrated for each experiment according to the operating pressure	Brooks Instruments Emerson Electric , Ltd Stockport, SK6 25R
HPS & LPS High and Low pressure Separators	HPS is a 316 stailess steal cylindrical tube designed for 250 bar pressure rating. It is used to receive the produced fluids from ISC process via the exit of the combustion tube. Primary separation stage is done in HPS. LPS is also made of 316 stainless steel and it is designed to work at 50 bar operating pressure. It works as second and final stage of fluid separation.	University of Bath, School of chemical Engineering (workshops)
PRVLs Pressure Regulator for liquid 44-2300 series, spring loaded	The system contains two PRVLs . PRVL1 is located on liquid discharge line from HPS and used to throttle liquid pressure to less than 30 bar (LPS working pressure). PRVL2 is located on the discharging liquid line from LPS. It is used to reduce the liquid pressure to the atmospheric pressure for samples collecting.	Tescom Corporation

Further Equipment Specification and manufactures.

Equipment Details	*Manufacturers*
Ball valves 1 / 4'' Swagelok series 40	Bristol Valves and fitting Bristol UK
Cement Portland	Castle Cement Ltd, Birmingham UK
Check Valves 1 / 4'' Swaglok series C	Bristol Valves and fitting
Clay Supreme china clay	English China Clay Ltd, St. Austell, Cornwall
Computer hardware	National Instrument Ltd.
Computer software -Labview-	National Instrument
Filters 1/4'' Swaglok	Bristol Valves and fittings
Gas chromatograph Type 8500	Perkin Elmer Ltd,
Gas cylinders (N2, O2)	BOC Bristol
Gas cylinders regulators	BOC Bristol
Vermiculite insulation (magnesium aluminium iron sulphate)	Dupre Vermiculite Hertford
Wet test meter type (DM3D, 600 L/hr max., 0.1 bar	Alexander Wright & Co. Ltd Sutton, Surrey
Buckland sand W50 and W150	Trottiscliffe Ltd Kent

Appendix D

STARS SIMULATION INPUT FILE

```
***------------------------------------------------------------
**      1D COMBUSTION TUBE TEST No.RUN-8. Australian light oil.
**      ========================================
**------------------------------------------------------------

** Special Features:
** 1) 1D vertical combustion tube
** 2) Four hydrocarbon components: three liquid C11+, C6-10, C1-5 and one solid.
**      Stocktank stabilized oil is used and CH4 composition is negligible.
** 3) Two non-condensible gases: oxygen & CO gases.
** 4) Four chemical reactions:
**    (a) cracking of heavy oil to light oil and coke,
**    (b) C11+ heavy oil burning,
**    (c) C6-10 light oil burning,
**    (d) COKE burning.
** 5) High initial pressure (70 bar, 7000 Kpa, 1015.266psia) and 65 oF (149 oF) Temperature.
** 6) Injection end is heated externally, ignition temperature 350 oC (662 oF).
** 7) porsity: 36.6%   Permeability: 1600 mD
** 8) Water saturation: 50%          Oil Saturation: 45% and
**    5% gas saturation assumed nitrogen the intial conditions.
** 9) Simulation stops when producing ends after 12 hours or
**    when the combustion fron reaches the end of combustion tube.


** ============== INPUT/OUTPUT CONTROL ==========================

filename output index-out main-results-out  ** Use default file names

*title1 '1D LIGHT OIL COMBUSTION TUBE TEST RUN No. 8'
*title2 'CLAIR Oil PVT Characterization'

*inunit field except  1 1  ** hrs instead of days
          except 11 1  ** ft3 instead of bbl
*OUTUNIT LAB
**CHECKONLY
*outprn *grid pres sw  so sg temp y x solconc obhloss viso
*outprn *well *all
*wrst 300  *wprn *grid 300  *wprn *iter 300

outsrf grid pres sw so sg temp y x w solconc obhloss
        masdenw masdeno  masdeng pcow pcog visw viso visg
        krw kro krg kvalyw kvalyx cmpdenw cmpdeno cmpvisw
        cmpviso cmpvisg cchloss

outsrf well component 5  7  8

outsrf special blkvar temp 0 1        ** T history, block 1
```

```
 blkvar temp 0 4      **    "   block 4
 blkvar temp 0 8      **    "   block 8
 blkvar temp 0 12     **    "
 blkvar temp 0 16     **    "
 blkvar temp 0 20     **    "
 blkvar temp 0 24     **    "
 blkvar temp 0 28     **    "
 blkvar temp 0 32     **    "
 blkvar temp 0 36     **    "
 blkvar temp 0 40     **    "
 blkvar temp 0 44     **    "
 blkvar temp 0 48     **    "
 blkvar temp 0 52     **    "   block 52
 blkvar temp 0 56     **    "
 blkvar temp 0 60     **    "
 blkvar temp 0 64     **    "
 blkvar temp 0 68     **    "
 blkvar temp 0 72     **    "   block 72
 blkvar temp 0 76     **    "
 blkvar temp 0 80     **    "
 blkvar temp 0 84     **    "
 blkvar temp 0 88     **    "
 blkvar temp 0 92     **    "
 blkvar temp 0 96     **    "
 blkvar temp 0 100    **    "
 blkvar temp 0 104    **    "
 blkvar temp 0 108    **    "
 blkvar temp 0 112    **    "
 blkvar temp 0 116    **    "
 blkvar temp 0 120    **    "
 blkvar temp 0 124    **    "   block 124
 blkvar temp 0 128    **    "   block 128
 avgvar temp 0       ** average T in tube
 blkvar sw 0 1       ** Sw history, block 1
 blkvar sw 0 4       ** Sw history, block 4
 blkvar sw 0 8       ** Sw history, block 8
 blkvar sw 0 16      ** Sw -
 blkvar sw 0 24      ** Sw -
 blkvar sw 0 32      ** Sw -
 blkvar sw 0 40      ** Sw -
 blkvar sw 0 48      ** Sw -
 blkvar sw 0 56      ** Sw -
 blkvar sw 0 64      ** Sw history, block 64
 blkvar sw 0 72      ** Sw -
 blkvar sw 0 80      ** Sw -
 blkvar sw 0 88      ** Sw -
blkvar sw 0 96       ** Sw -
 blkvar sw 0 104     ** Sw -
 blkvar sw 0 112     ** Sw -
 blkvar sw 0 120     ** Sw history, block 120
 blkvar sw 0 128     ** Sw history, block 128
 blkvar so 0 1      ** So history, block 1
blkvar so 0 4       ** So history, block 4
 blkvar so 0 8      ** -
 blkvar so 0 16     ** -
 blkvar so 0 24     ** -
 blkvar so 0 40     ** -
blkvar so 0 48      ** -
```

```
 blkvar so 0 56        ** -
  blkvar so 0 64       ** -
 blkvar so 0 72        ** So history, block 72
 blkvar so 0 80        ** -
blkvar so 0 88        ** -
blkvar so 0 96        ** -
blkvar so 0 104       ** -
blkvar so 0 112       ** -
 blkvar so 0 120       ** So history, block 120
 blkvar so 0 124       ** So history, block 124
 blkvar so 0 128       ** So history, block 128
blkvar sg 0 1         ** Sg history, block 1
blkvar sg 0 4         ** Sg history, block 4
blkvar sg 0 8         ** Sg history, block 8
blkvar sg 0 16        ** Sg history, block 16
blkvar sg 0 24        ** -
blkvar sg 0 32        ** -
blkvar sg 0 40        ** -
blkvar sg 0 48        ** -
blkvar sg 0 56        ** -
blkvar sg 0 64        ** -
blkvar sg 0 72        ** -
blkvar sg 0 80        ** -
blkvar sg 0 88        ** -
blkvar sg 0 96        ** -
blkvar sg 0 104       ** -
blkvar sg 0 112       ** -
blkvar sg 0 120       ** Sg history, block 120
blkvar sg 0 128       ** Sg history, block 128
blkvar pres 0 128     ** block pressure, 128
blkvar pres 0 90      ** block pressure, 90
blkvar pres 0 60      ** block pressure, 60
blkvar pres 0 30      ** block pressure, 30
blkvar pres 0 4       ** block pressure, 4
blkvar pres 0 1       ** block pressure, 1
blkvar solconc  9 16    ** Coke conc,   "
blkvar y 5 16         ** y(oxygen),   "

** ========== GRID AND RESERVOIR DEFINITION ==========

*grid *cart 1 1 64  ** 64 blocks in the K direction (normal vertical)
  ** Tube I.D. = 10 cm.  Cross-sectional area is pi*(d/2)**2
**  = 78.54 cm2 = L*L.  so equivalent block side is
** L = 8.86227 cm (0.28708 ft).
** Total tube length is 125 cm;
** block size = 125/64 = .064 ft
*di *con 0.28708   *dj *con 0.28708   *dk *con 0.064
*permi *con 1004    *permj *equalsi    *permk *equalsi
  *rockcp 35.02  *thconr 1 *thconw 0.36 *thcono 0.077 *thcong 0.0833
*cpc 4.06
```

```
** ========== FLUID DEFINITIONS ==========

*model 9 8 6  ** Number of noncondensible gases is numy-numx = 2
               ** Number of solid components is ncomp-numy = 1
               ** N2 & CO2 soluble in the liquid petroleum phase
               **  O2 & CO only the gas phase insoluble in the liquid petroleum phase

*compname 'WATER'  'C11+'  'C6-10'  'C1-5' 'CO2'  'N2'   'O2' 'CO' 'COKE'
**        ______ _______ _______ _____ _______ _____ _____ ____ _____
*cmm       18    329.36  115.98  72.15  44.01 28.01   32  28.01
*pcrit    3155   196.90  363.09 488.1  1071.0  500   730  507.5
*tcrit   705.7  1478.9   548.2  385.47  87.56 -232.84 -181.72 -220.78

*avg      0  3.926e-6 3.926e-6 2.166e-6 2.1267e-4 2.1960e-4 2.1960e-4 2.1960e-4
*bvg      0  1.102    1.102    0.943    0.721    0.721  0.702    0.702
*avisc    0  4.02e-4  4.02e-4  4.02e-4  4.02e-4  4.02e-4
*bvisc    0   1621.6  1621.6   6121.6   6121.6   6121.6

*molden   0     0.2024    0.1309  0.0481  0.6623  0.6944  ** LBMOLE/FT3
*cp       0      4e-6     4.5e-6  5e-6    7e-6    7.5e-6
*ct1      0     1.496e-4  2.839e-4 2.839e-4 2.839e-4 2.839e-4
**              55.191     44.189  39.368     LB/FT3
**              11.6       39.1    44.8       API

** ------------------------------------------------------------
** CHEMICAL REACTION 1 - Cracking:  C11+ ->  C6-C10 + Coke
*compname 'WATER' 'C11+'  'C6-10'  'C1-5' 'CO2'  'N2' 'O2'   'CO' 'COKE'
**        ______ _______ _______ _____ _____ _____ _____ ____ _____
*storeac  0      1      0       0     0     0     0    0    0
*stoprod  0      0  0.20735  0       0     0     0     0  0 21.93749
*freqfac 2.0e5  *eact 27000  *renth 0
** ------------------------------------------------------------
** CHEMICAL REACTION 2 - Cracking:  C11+ ->  C1-C5 + Coke
**compname 'WATER' 'C11+'  'C6-10'  'C1-5' 'CO2'  'N2' 'O2'   'CO' 'COKE'
**        ______ _______ _______ _____ _____ _____ _____ ____ _____
**storeac  0      1      0           0     0     0     0    0    0
**stoprod  0      0      0      0.1356     0     0     0    0 23.0613
**freqfac 2.1e5  *eact 25000  *renth 0
** ------------------------------------------------------------
** CHEMICAL REACTION 3- Heavy Oil Burning:  C11+ + O2 -> H20 + CO/CO + energy
*compname 'WATER' 'C11+'  'C6-10'  'C1-5' 'CO2'  'N2' 'O2'  'CO' 'COKE'
**        ______ _______ _______ _____ _____ _____ _____ ____ _____
*storeac  0      1      0       0     0     0  20.94472 0    0
*stoprod 18.93632  0      0       0     0     0     0  22.95311 0
*freqfac 3.020e10  *eact 16500  *renth 8774.06
** ------------------------------------------------------------
** CHEMICAL REACTION 4- Light Oil Burning:  C6-C10 + O2 -> H20 + CO + energy
*compname 'WATER' 'C11+'  'C6-10'  'C1-5' 'CO2'  'N2'  'O2'  'CO' 'COKE'
**        ______ _______ _______ _____ _____ _____ _____ ____ _____
*storeac  0      0      1       0     0     0  8.970302 0    0
*stoprod 10.35473  0      0       0     0     0     0  7.585879 0
*freqfac 3.020e10  *eact 17500  *renth 3685.33
** ------------------------------------------------------------
```

```
** CHEMICAL REACTION 5- Hydrocarbon Gas Burning:  C1-C5 + O2 -> H20 + CO + energy
*compname 'WATER' 'C11+'  'C6-10'  'C1-5' 'CO2'  'N2'  'O2'  'CO' 'COKE'
**
*storeac   0         0     0      1    0    0  5.792082 0       0
*stoprod 6.685998  0     0      0    0    0        0  4.898167  0
*freqfac 3.020e10  *eact 17000  *renth 185.3466
** ---------------------------------------------------------------
** CHEMICAL REACTION 6- Coke Burning:  Coke + O2 -> H20 + CO2 + energy
*compname 'WATER' 'C11+'  'C6-10'  'C1-5' 'CO2'  'N2' 'O2' 'CO' 'COKE'
**


*storeac   0     0      0      0    0    0   1.4   0     1
*stoprod   0.8   0      0      0    1    0   0     0     0
*freqfac 3.0e5  *eact 6500  *renth 437.19
** ---------------------------------------------------------------
** CHEMICAL REACTION 5 - Gas burning:  CH4 + 2O2 -> 2H20 + CO2 + energy
** *compname  'H2O'  'C7+'   'C2-C6'  'CH4'  'CO2'  'O2'  'COKE'
** *compname 'H2O' 'C11+'  'C6-10'  'C1-5' 'CO2'  'N2' 'O2' 'CO' 'COKE'
**      ------ ------- ------- ------- ------ ------ -----
** *storeac  0     0      0      1     0    2      0
** *stoprod  2     0      0      0     1    0      0
** *freqfac      3.020e10
** *eact     59450
** *renth        502.533     ** Reaction Enthalpy  BTU/lbmole
** ---------------------------------------------------------------
** CHEMICAL REACTION 5 - Carbon Monoxide burning:  CO + 0.5 O2 -> CO2 + energy
*compname 'WATER' 'C11+'  'C6-10'  'C1-5' 'CO2'  'N2' 'O2' 'CO' 'COKE'
**      ------ ------- ------- ------- ------ ------ -----  ------  ------
*storeac  0     0      0      0     0    0     0.5    1      0
*stoprod  0     0      0      0     1    0     0      0      0
*freqfac   1.5e5
** *freqfac   8.064E8
*eact     7550
*renth     2.838E5
*solden 4.4

** Pseudocomponent K value tables for pressures 500 psi & 6500 psi 100 F to 1300 F be 100 deg
intervals
*kvtablim 500 3250 100 1300

*kvtable 2   ** K value table for C11+
1.320E-07  8.800E-08  6.600E-08 5.280E-08 4.400E-08 3.772E-08 3.300E-08 2.933E-08 2.640E-08
2.400E-08 2.200E-08 2.031E-08
5.453E-06 3.635E-06 2.727E-06 2.181E-06 1.818E-06 1.558E-06 1.363E-06 1.212E-06 1.091E-06
9.915E-07 9.088E-07 8.389E-07
8.461E-05 5.641E-05 4.230E-05 3.384E-05 2.820E-05 2.417E-05 2.115E-05 1.880E-05 1.692E-05
1.538E-05 1.410E-05 1.302E-05
6.938E-04 4.626E-04 3.469E-04 2.775E-04 2.313E-04 1.982E-04  1.735E-04  1.542E-04  1.388E-04
1.262E-04  1.156E-04  1.067E-04
3.671E-03  2.447E-03  1.835E-03  1.468E-03  1.224E-03  1.049E-03  9.176E-04  8.157E-04   7.341E-
04  6.674E-04  6.118E-04  5.647E-04
1.418E-02  9.454E-03  7.090E-03  5.672E-03  4.727E-03  4.052E-03  3.545E-03  3.151E-03   2.836E-
03  2.578E-03  2.363E-03  2.182E-03
4.340E-02  2.893E-02  2.170E-02  1.736E-02  1.447E-02  1.240E-02  1.085E-02  9.644E-03   8.679E-
03  7.890E-03  7.233E-03  6.676E-03
```

.112E-01 7.413E-02 5.560E-02 4.448E-02 3.707E-02 3.177E-02 2.780E-02 2.471E-02 2.224E-02 2.022E-02 1.853E-02 1.711E-02
2.481E-01 1.654E-01 1.241E-01 9.925E-02 8.271E-02 7.089E-02 6.203E-02 5.514E-02 4.962E-02 4.511E-02 4.135E-02 3.817E-02
4.960E-01 3.307E-01 2.480E-01 1.984E-01 1.653E-01 1.417E-01 1.240E-01 1.102E-01 9.920E-02 9.018E-02 8.267E-02 7.631E-02
9.073E-01 6.048E-01 4.536E-01 3.629E-01 3.024E-01 2.592E-01 2.268E-01 2.016E-01 1.815E-01 1.650E-01 1.512E-01 1.396E-01
1.543044 1.029E+00 7.715E-01 6.172E-01 5.143E-01 4.409E-01 3.858E-01 3.429E-01 3.086E-01 2.806E-01 2.572E-01 2.374E-01
2.470692 1.647E+00 1.235E+00 9.883E-01 8.236E-01 7.059E-01 6.177E-01 5.490E-01 4.941E-01 4.492E-01 4.118E-01 3.801E-01
*kvtable 3 ** K value table for C6-10
0.0019 0.0013 0.0010 0.0008 0.0006 0.0005 0.0005 0.0004 0.0004 0.0003 0.0003 0.0003
0.0147 0.0098 0.0073 0.0059 0.0049 0.0042 0.0037 0.0033 0.0029 0.0027 0.0024 0.0023
0.0655 0.0437 0.0328 0.0262 0.0218 0.0187 0.0164 0.0146 0.0131 0.0119 0.0109 0.0101
0.2068 0.1378 0.1034 0.0827 0.0689 0.0591 0.0517 0.0459 0.0414 0.0376 0.0345 0.0318
0.5135 0.3424 0.2568 0.2054 0.1712 0.1467 0.1284 0.1141 0.1027 0.0934 0.0856 0.0790
1.0743 0.7162 0.5372 0.4297 0.3581 0.3070 0.2686 0.2387 0.2149 0.1953 0.1791 0.1653
1.9790 1.3193 0.9895 0.7916 0.6597 0.5654 0.4947 0.4398 0.3958 0.3598 0.3298 0.3045
3.3085 2.2057 1.6542 1.3234 1.1028 0.9453 0.8271 0.7352 0.6617 0.6015 0.5514 0.5090
5.1286 3.4190 2.5643 2.0514 1.7095 1.4653 1.2821 1.1397 1.0257 0.9325 0.8548 0.7890
7.4866 4.9911 3.7433 2.9946 2.4955 2.1390 1.8716 1.6637 1.4973 1.3612 1.2478 1.1518
10.4114 6.9410 5.2057 4.1646 3.4705 2.9747 2.6029 2.3137 2.0823 1.8930 1.7352 1.6018
13.9149 9.2766 6.9575 5.5660 4.6383 3.9757 3.4787 3.0922 2.7830 2.5300 2.3192 2.1408
17.9943 11.9962 8.9972 7.1977 5.9981 5.1412 4.4986 3.9987 3.5989 3.2717 2.9991 2.7684
*kvtable 4 ** K value table for C1-5
0.0318 0.0212 0.0159 0.0127 0.0106 0.0091 0.0079 0.0071 0.0064 0.0058 0.0053 0.0049
0.1479 0.0986 0.0739 0.0591 0.0493 0.0422 0.0370 0.0329 0.0296 0.0269 0.0246 0.0227
0.4590 0.3060 0.2295 0.1836 0.1530 0.1311 0.1147 0.1020 0.0918 0.0834 0.0765 0.0706
1.0947 0.7298 0.5473 0.4379 0.3649 0.3128 0.2737 0.2433 0.2189 0.1990 0.1824 0.1684
2.1785 1.4523 1.0893 0.8714 0.7262 0.6224 0.5446 0.4841 0.4357 0.3961 0.3631 0.3352
3.8075 2.5383 1.9038 1.5230 1.2692 1.0879 0.9519 0.8461 0.7615 0.6923 0.6346 0.5858
6.0438 4.0292 3.0219 2.4175 2.0146 1.7268 1.5110 1.3431 1.2088 1.0989 1.0073 0.9298
8.9153 5.9435 4.4576 3.5661 2.9718 2.5472 2.2288 1.9812 1.7831 1.6210 1.4859 1.3716
12.4202 8.2801 6.2101 4.9681 4.1401 3.5486 3.1050 2.7600 2.4840 2.2582 2.0700 1.9108
16.5347 11.0231 8.2674 6.6139 5.5116 4.7242 4.1337 3.6744 3.3069 3.0063 2.7558 2.5438
21.2194 14.1463 10.6097 8.4878 7.0731 6.0627 5.3049 4.7154 4.2439 3.8581 3.5366 3.2645
26.4251 17.6168 13.2126 10.5701 8.8084 7.5500 6.6063 5.8723 5.2850 4.8046 4.4042 4.0654
32.0977 21.3985 16.0488 12.8391 10.6992 9.1708 8.0244 7.1328 6.4195 5.8359 5.3496 4.9381
*kvtable 5 ** K value table for CO2
2.4914 1.6609 1.2457 0.9966 0.8305 0.7118 0.6229 0.5536 0.4983 0.4530 0.4152 0.3833
6.8249 4.5500 3.4125 2.7300 2.2750 1.9500 1.7062 1.5167 1.3650 1.2409 1.1375 1.0500
14.3411 9.5607 7.1705 5.7364 4.7804 4.0975 3.5853 3.1869 2.8682 2.6075 2.3902 2.2063
25.3553 16.9035 12.6776 10.1421 8.4518 7.2444 6.3388 5.6345 5.0711 4.6101 4.2259 3.9008
39.8103 26.5402 19.9052 15.9241 13.2701 11.3744 9.9526 8.8467 7.9621 7.2382 6.6351 6.1247
57.4057 38.2705 28.7029 22.9623 19.1352 16.4016 14.3514 12.7568 11.4811 10.4374 9.5676 8.8317
77.7156 51.8104 38.8578 31.0862 25.9052 22.2045 19.4289 17.2701 15.5431 14.1301 12.9526 11.9562
100.2720 66.8480 50.1360 40.1088 33.4240 28.6491 25.0680 22.2827 20.0544 18.2313 16.7120 15.4265
124.6166 83.0777 62.3083 49.8466 41.5389 35.6047 31.1541 27.6926 24.9233 22.6576 20.7694 19.1718
150.3284 100.2189 75.1642 60.1314 50.1095 42.9510 37.5821 33.4063 30.0657 27.3324 25.0547 23.1274
177.0362 118.0241 88.5181 70.8145 59.0121 50.5818 44.2590 39.3414 35.4072 32.1884 29.5060 27.2363

204.4214 136.2809 102.2107 81.7685 68.1405 58.4061 51.1053 45.4270 40.8843 37.1675
34.0702 31.4494
232.2161 154.8107 116.1080 92.8864 77.4054 66.3475 58.0540 51.6036 46.4432 42.2211
38.7027 35.7256
*kvtable 6 ** K value table for N2
27.0188 18.0125 13.5094 10.8075 9.0063 7.7197 6.7547 6.0042 5.4038 4.9125 4.5031 4.1567
38.0483 25.3655 19.0241 15.2193 12.6828 10.8709 9.5121 8.4552 7.6097 6.9179 6.3414 5.8536
48.9645 32.6430 24.4822 19.5858 16.3215 13.9898 12.2411 10.8810 9.7929 8.9026 8.1607 7.5330
59.4225 39.6150 29.7113 23.7690 19.8075 16.9779 14.8556 13.2050 11.8845 10.8041 9.9038 9.1419
69.2638 46.1759 34.6319 27.7055 23.0879 19.7897 17.3160 15.3920 13.8528 12.5934 11.5440
10.6560
78.4340 52.2893 39.2170 31.3736 26.1447 22.4097 19.6085 17.4298 15.6868 14.2607 13.0723
12.0668
86.9345 57.9563 43.4672 34.7738 28.9782 24.8384 21.7336 19.3188 17.3869 15.8063 14.4891
13.3745
94.7952 63.1968 47.3976 37.9181 31.5984 27.0843 23.6988 21.0656 18.9590 17.2355 15.7992
14.5839
102.0592 68.0395 51.0296 40.8237 34.0197 29.1598 25.5148 22.6798 20.4118 18.5562 17.0099
15.7014
108.7741 72.5161 54.3871 43.5097 36.2580 31.0783 27.1935 24.1720 21.7548 19.7771 18.1290
16.7345
114.9876 76.6584 57.4938 45.9951 38.3292 32.8536 28.7469 25.5528 22.9975 20.9068
19.1646 17.6904
120.7452 80.4968 60.3726 48.2981 40.2484 34.4986 30.1863 26.8323 24.1490 21.9537 20.1242
18.5762

126.0891 84.0594 63.0445 50.4356 42.0297 36.0254 31.5223 28.0198 25.2178 22.9253 21.0148
19.3983

** Reference conditions
*prsr 14.7 *temr 77 *psurf 14.65 *tsurf 62

** ========== ROCK-FLUID PROPERTIES ==========
*rockfluid

*swt ** Water-oil relative permeabilities

** Sw	Krw	Krow
0.31	0.0	1.0
0.3323	0.0037	0.8869
0.3547	0.0104	0.7784
0.3769	0.0191	0.6747
0.3992	0.0294	0.576
0.4215	0.041	0.4828
0.4439	0.0539	0.3951
0.4662	0.068	0.3136
0.5108	0.0991	0.1707
0.5331	0.116	0.1109
0.5554	0.1339	0.0603
0.5777	0.1525	0.0213
0.6800	0.2479	0.00
0.7600	0.3325	0.00
0.8400	0.425	0.00
0.9200	0.5247	0.00
1.0000	0.6313	0.00

** 0.752 0.256 0.0

```
*slt  ** Liquid-gas relative permeabilities

**  Sl      Krg     Krog
** ----    -------  -------
   0.31    0.49     0.00
   0.43    0.3344   0.00
   0.5909  0.1722   0.0008
   0.7139  0.0844   0.0481
   0.8364  0.0276   0.2577
   0.9591  0.0017   0.7513
   1.000   0.000    1.000


 ** *swr 0.25  *sorw 0.25  *sgr 0.12 *sorg 0.2

** ================ INITIAL CONDITIONS ========================
*initial
*pres *con 1015.266        ** high initial pressure 70 bar (7000 kPa or 1015.266 psi)
*sw *con 0.50              ** initial water saturation is 0.50
*so *con  0.45             ** initial gas saturation is 0.05

*temp *con 140             ** Reservoir Bed Temperature  65 oC (149 oF)



** Gas in tube at the initial conditions  is N2 with small concetration of C1-5
** at equilibrium with the liquid petroleum phase.

**                        'H2O' 'C11+'  'C6-10'  'C1-5' 'CO2'  'N2'     'O2'    'CO'  'COKE'
   *molefrac *gas *con                    3*0.0   0.003  0.0    0.997      0.0     0.0

** *molefrac *gas *con  5*0.0 0.79 0.21 0.0
**  Initial petroleum phase fraction are:  C11+ = 0.419300   C6-10 = 0.276600   C1-5 = 0.304100
** After equilibization with the N2 gas phase the Nitrogen fraction in the oil phase is 0.04 and
** the hydrocarbon fraction are: C11+ =0.402528   C6-10 =0.265536   C1-5 = 0.291936

**                      'H2O' 'C11+'       'C6-10'   'C1-5'      'CO2'  'N2'  'O2'  'CO' 'COKE'
*molefrac *oil *con          0.0     0.385756  0.254472  0.279772  0.0     0.08

** *molefrac *oil *con  0.0     0.419300  0.276600 0.304100  0.0     0.0

** ================ NUMERICAL CONTROL ========================

*numerical  ** All these can be defaulted.  The definitions
        ** here match the previous data.

*maxsteps 1800  *north 10  *newtoncyc 20  *itermax 15

*norm    press 15   satur .1   temp 40  y .1   x .1
*converge press .15  satur .002  temp .5  y .002  x .002
**ncuts 30
*run
```

```
** ============== RECURRENT DATA ======================

time 0  dtwell  .005

 well 1 'INJECTOR'  injector 1
  operate gas  2.219  **100 cm3/min       ** Injection Rate 2.219 ft3/hr (8m3/m2hr)
    perf 1 ** i  j  k  wi(gas)
           1  1 64   5.54
  *incomp gas  5*0.0   0.79   0.21   0.0
 **incomp water  1.0 0.0 0.0 0.0
   *tinjov 140
   **tinjw 70

well 2 'PRODUCER'  producer 2
 operate bhp 1015.266
monitor temp 1800 stop
  geometry k -1 1 1 0          ** Linear pressure drop at tube end
  perf geo 2  ** i  j  k
            1  1  1
*shutin 1

heatr ijk 1 1 64  550         ** Use external heaters to raise the temperature
heatr ijk 1 1 63  550         ** Use external heaters to raise the temperature
**heatr ijk 1 1 126  550        ** Use external heaters to raise the temperature
time .15
open 1
time .2

heatr con 0     ** Shut off external heaters

time 0.5
outsrf grid none
time 1
outsrf grid none
time 1.5
      outsrf grid pres sw so sg temp y x w solconc obhloss
              masdenw masdeno  masdeng pcow pcog visw viso visg
              krw kro krg kvalyw kvalyx cmpdenw cmpdeno cmpvisw
              cmpviso cmpvisg cchloss
time 2.0
outsrf grid none
time 2.5
      outsrf grid none
time 3.0
outsrf grid none
time 3.5
      outsrf grid none
time 4.0
outsrf grid none
time 4.5
      outsrf grid none
time 5.0
outsrf grid none
time 5.5
      outsrf grid pres sw so sg temp y x w solconc obhloss
              masdenw masdeno  masdeng pcow pcog visw viso visg
```

```
   krw kro krg kvalyw kvalyx cmpdenw cmpdeno cmpvisw
            cmpviso cmpvisg cchloss
time 6.5
outsrf grid none
time 7
      outsrf grid none
time 8
outsrf grid none
time 9
      outsrf grid none
time 10
outsrf grid none
time 11
outsrf grid none
time 12
outsrf grid none
time 13
time 14
      outsrf grid pres sw so sg temp y x w solconc obhloss
            masdenw masdeno  masdeng pcow pcog visw viso visg
            krw kro krg kvalyw kvalyx cmpdenw cmpdeno cmpvisw
            cmpviso cmpvisg cchloss


stop
```

UNIVERSITY OF BATH
SCHOOL OF CHEMICAL ENGINEERING

Risk Assessment Form

Name of undergraduate/postgraduate student(s)/researcher(s)

T. Young ..... S. EL-Usta ..... S. REN .....

S. Duygun ....

Supervisor(s) DR. M. GREAVES / DR. R. R. RATHBONE

Supervisors should identify areas of work in the following risk categories

A Those where work may not be undertaken without Senior Supervision

B Those where work may not be started without Supervisor's advice

C Those with risks (other than in categories A and B) where extra care must be observed, but where it is considered that workers are adequately trained and competent in the procedures involved

The nature of the risks should be defined, *i.e.* toxicity, explosion, high-voltage, lasers, flammability, high/low pressure, vacuum, high/low temperature, *etc.*

Instructions and advice should include the method of work and the safeguards to be used. Detailed assessment to be attached.

The person who is to supervise A and B risks should be identified.

Work	Hazard	Category	Supervisor
High Pressure Oxidation/ Combustion Tube Experiment	*High pressure, Flammability of crude oils*	*C*	*M.Greaves* R.R.Rathbone

Supervisor(s)'s signature ..... M. Greaves .....

Signature of undergraduate/postgraduate student/researcher having read and understood the contents of the form

..... S. El-Usta ....

..... Researcher ....

Date 21.8.96

cont...

	Pressure let down is via manual control
Water	Same as above, but pressure let down controlled automatically by computer
Gases	Same as above if nitrogen supply remains operative, otherwise combustion tube remains isolated until nitrogen supply is reconnected
Fume cupboard	Discontinue toluene extraction and close fume cupboard

Training required / given

Present research personnel were responsible for design and commissioning of the combustion tube facility. Full training will be given to new research personnel

Special supervision required

None. Only experienced / trained research personnel allowed to operate combustion tube facility

Assessment Personnel

Name:	M. Greaves	Signature: M. Greaves
Position:	Reader	Date: 21.8.96
Name:	R.R. Rathbone	Signature:
Position:	Lecturer	Date: 21 Aug 96
Name:	S .R. Ren	Signature:
Position:	Research Officer	Date: 20/8/96
Name:	S.R. Chawla-Duggan	Signature: S. R. Chawla-Duggan
Position:	Research Technician	Date: 21/8/1996
Name:	T. Young	Signature:
Position:	Research Student	Date: 21/8/96
Name:	S. El-Usta	Signature:
Position:	Research Student	Date: 21/8/96
Name:	D. Shallcross	Signature:
Position:	Visiting Professor	Date: 22/8/96

cont...

COSHH
RISK ASSESSMENT (CHEMICAL)

Project/Research Title:

Air Injection for Improved Oil Recovery
High Pressure Oxidation / Combustion Tube Facility

Name of Supervisor: **Dr. M. Greaves**

Start Date: 20/08/1996

Location of Work: 4 West Safety Cell, 4W 1.9 (supervisory computer)

Hazardous Substances	**Quantity**	**Safety Data Sheet**
Toluene (extraction solvent)	50 ml	attached
Trichloroethane (solvent)	50 ml	attached
Crude oil	4.5 litre	see below
Kaowool ceramic fibre insulation blanket	1 m^2	attached

Nature of the Hazards (crude oils)

Crude oils: Flash point ~ 100 °C, suspected carcinogenic, flammable, other details on data sheet for crude oil (attached)

Reactive hazards

Crude oils are highly combustible, reactivity increases with oxygen concentration. Fire and Explosion Index (Dow), FEI = 93.4, which is of intermediate classification.

Experimental Procedures/system of work to be followed

<u>Combustion Tube Reactor Preparation</u>

Verify that all wall thermocouples are in place: each thermocouple should be held in place next to its associated band heater (towards the bottom side), the securing screws should be tightened only to finger tight.

(1) Verify that each band heater is working and that the wiring is not exposed (the ceramic rings used for this electrical insulated are brittle and easily break). Replace any label on the connection leads that may blackened through excess heating.

(2) Bolt into position the bottom tube flange. It is best to use a new gasket for each run. This should be sealed on both sides using Silicone sealant. Each of the six bolts should be tightened to 60Nm. Ensure that the bolt heads face away from the tube, the nuts on the inside, with washers on both sides of the flange.

(3) Remove the large seal nut and the V-ring stock from the bottom flange of the shell. Lower the combustion tube (CT) and insulating block into the shell and guide the CT exit line through the bottom flange, ensuring that the bolt heads are located in the

cont...

recesses in this block. Slide the V-ring stock onto the exit line of the tube and re-pack the seal nut; first goes the thinnest followed by three more and finally the thickest and bolt into position the seal nut.

(4) Tip the shell to about 45° using the small portable crane and insert the axial thermocouple. Clean the tapered thread and use PTFE tape before screwing this into place. Ensure that the valve at the tube exit is closed.

(5) Drop the filter/support into the top of the CT with the axial thermocouple through its center. The mesh on this support is likely to get damaged during the postmortem and may need a new mesh for each run.

(6) Fill the CT with the reservoir mixture. Make a hole in a plastic bin liner. Tape this over the top of the tube to prevent any spillage. Drop in about 0.50 kg at a time. Use the special packing tools to ensure even packing of the mixture in the tube. Repeat this until the mixture just covers the axial thermocouple. Add a small amount of pure linseed oil on top of the sandpack to improve ignition.

(7) Remove the plastic bin liner and clean the top flange of oil and sand. Bolt into place the top flange as in step 2.

(8) Fill the annulus between the shell and the CT with vermiculite to the top flange surface of the CT. Connect the band heater wiring first followed by the thermocouples laying this wiring carefully around the tube inlet line. These wires will need to be coaxed so that they do not get caught when the shell flange is bolted back into position.

(9) Using the outdoor crane slowly lower the shell flange into position and align the bolts head down, screwing on the nuts from the top. Full washers on the top and washers with cut-away edges underneath. This is to ensure that no damage is caused to the welding joint of the shell. Using the 5X torque multiplier, torque each bolt down to 1250 Nm.

(10) Lower the shell into the safety cell. Make sure no body stands inside the Safety cell before the shell is lowered into its position on the cradle. In the safety cell, the best way to position the shell cradle is to lever it using a scaffolding pole as a crow bar. When removing the shell from the safety shell, using crane to lift some weight of the shell and then move the cradle.

(11) Connect all pipe work, thermocouples and band heater wiring. Connect the earthing wires for the band heaters and ignitor to the tube inlet line. Thermocouple connections can be checked using the IscView software.

General Notes on shell movement

When moving the shell from one cradle to another, ensure that the wheels are pointing in the direction you wish to push the cradle. This is particularly important in the safety cell as the floor is uneven. When moving the shell on the rails, for example to remove the top flange, the only way to reverse the direction of the wheels is to lift the shell and cradle together up a little bit, turn the wheels around and then slowly lower them back onto the rails.

cont...

Operating Procedures

After transfer of the assembled CT and shell to the Safety cell and make all the connections, secure the roof-hatch, and post "NO ADMITTANCE" signs around the Safety cell area. Load the LabView software and run IscView, then follow the instructions on the screen to

(1) Activate the ventilation blower (the switch is in the main laboratory)
(2) Turn on the cooling water to HP and LP separators.
(3) Turn on the power switch to the band heater transformers
(4) Turn on the power switch to solenoid-valve control board
(5) Set the required experimental parameters: tube pressure, initial reservoir temperature, ignition temperature and air flux.

After the CHECK-ALL list has been approved, the operation is then controlled by the computer remotely from the observation area of the Safety cell following the established procedures described below;

(1) **Pressurisation:** A stagewise pressurisation is carried out in both the CT and shell with nitrogen, in 2 bar stages. The differential pressure between the tube and shell is set always less than 2 bar. The maximum operating pressure is 240 bar.

(2) **Heating-up:** After pressurization, the band heaters are activated by a control program to raise the sand pack temperature evenly (axial thermocouple) to the required reservoir temperature (the process takes 30-60 minuets). Meanwhile, the ignitor is activated to raise the sandpack temperature at the CT inlet area to the ignition temperature required (about 120 °C for light oils and, extending to 300-350 °C for heavy oils).

(3) **Air injection and Combustion:** As the ignition temperature is achieved, air injection (oxygen and nitrogen mixture) is activated to the required flux. The reaction/combustion is then monitored by observing the axial temperatures and also the exit gas compositions (CO_2, CO, O_2 concentrations).

(4) **Air Injection and Reaction (Low temperature Reaction):** Air injection is commenced following achievement of the required reservoir temperature.
Reaction temperature and production gases are monitored as in (3)

(5) **Safety Control:** The system is monitored for the following scenarios that would require shut down to take place:

*Back Pressure Check: An unexpected rise in back pressure. This could be caused by some blockage in the gas lines after the HPS. Any large increase in pressure much greater than 2 bar would mean the pressure drop across the mass flow meters was reduced below the minimum required resulting in loss of injection flow control.

*Shell/Tube Differential Pressure Check: The shell and tube pressure difference is verified that it is well within safety limits of ±2 bar.

cont...

*Separator Level Check: Verify that the level detectors are below their maximum value. This may be caused by blockages or valve failure in the separator drain lines and would cause flooding in the gas lines.

*Injection line temperature: This is monitored (by TC1) to indicate any reverse flow burning from the combustion tube reactor. If the temperature is higher than 100 °C, shut-down will be implemented.

All of the above would cause to computer to carry out a controlled shut down. An emergency shut down will be implemented if an error occurs anywhere within the software or data acquisition hardware. The controlled shut-down and emergency shut-down may also be operator activated at any stage. In the case of failure of the computer system or the electrical power supply system, a manual shut-down can be applied by the operator.

(6) **Shut Down:** Many possibilities have to be taken into account (as listed above) when considering the method of shut down. The process has been designed using normal valve states to enable one method to take into account all reasonable scenarios.

***Controlled Shut Down**

The computer de-energises all the solenoid valves bringing all the air automated valves to there normal states and commands all currently running control tasks to begin their stop sequences. This shuts-in the high pressure side of the system, opening the shell side to the tube side (via AAV19) and the top of the tube to the bottom of the tube (via AAV3), allowing pressure equalisation throughout. Importantly the large volume of nitrogen in the shell acts to dilute any oxygen. Injection gas is immediately vented via AAV15. The pressure in the system is then decreased via the liquid production lines. SV20 and SV23 are energised opening AAV6 and AAV5 respectfully. The pressure is brought down using PRVL1 and PRVL2 as normal.

***Emergency shut down**

IscView causes an immediate exit, stopping the entire program at an instant, as it does so a small file is saved to disk detailing where or what, in the software or data acquisition hardware, an error was generated. The pulse pattern to the "watch dog" controller ends, cutting the power to the SVs and BHs. The operator is then instructed to commence a manual shut down. The overall effect then is one similar to that of a power cut.

***Manual Shut Down**

For manual shut down a separate air supply is used to open AAV6 and AAV5 using BV4 and BV5 respectfully. If any blockage occurs along this pressure let down path (the liquid lines from the HPS), PPRV6 and AAV4 can be controlled via CAR2 and BV2. Here the path is via the shell vent line. If a blockage occurs between the shell and the tube then PPRV5 and AAV2 (via CAR1 and BV1) must be used in conjunction with PPRV6 and AAV4 to let down the pressure in the shell and the tube separately. This process is monitored using PG7, PG8 and PG9

cont...

Containment / fume cupboard classification

(1) Combustion tube (reactor) is housed in Safety Cell (4 West)
(2) Reactor tube is contained in a pressure shell, containing insulation and inert gas (nitrogen)
(3) Combustion gases are discharged to atmosphere

Other safeguards / protective clothing

(1) No personnel allowed in the safety cell when combustion tube is in operation
(2) Combustion tube is operated remotely by computer
(3) Protective gloves, clothing and glasses to be worn when handing crude oil and partially combusted oil samples
(4) Toluene extraction to be carried out in fume cupboard
(5) Wear gloves, face mask and avoid contact with skin when handling the Kaowool ceramic blanket

Special monitoring required

Combustion tube is continuously monitored by control computer, but operator (observer) must maintain surveillance via supervisory computer (4W 1.9) throughout the experiment.

Waste disposal

Crude oil and produced oil to crude oil / solvent waste drums
Crude oil / sand waste to be sealed in plastic bags
Solvent to solvent waste drum
Kaowool insulation - dispose of as normal waste but avoid dust generation by sealing in bags

Action in case of loss of containment / accidental spillage

Dose crude oil spillage with adsorbent (dry sands)
Collect waste in plastic bags and seal
Clean area with water and detergent
Collect pieces of Kaowool blanket in bags and seal. Vacuum clean the area of Kaowool dust

Action in case of fire / explosion

Switch off electrical power to Safety cell to isolate the Combustion/Oxidation tube.
Operate carbon dioxide fire extinguisher.
Call Fire Brigade

Action in case of services failure

Electricity — Operation of combustion tube fails to safe condition and is isolated
Nitrogen purge is automatically connected to injection line

cont...

Attachments

Fig-1 Schematic Diagram of the High Pressure Air Injection Facility (Pressure and Flow Control System)

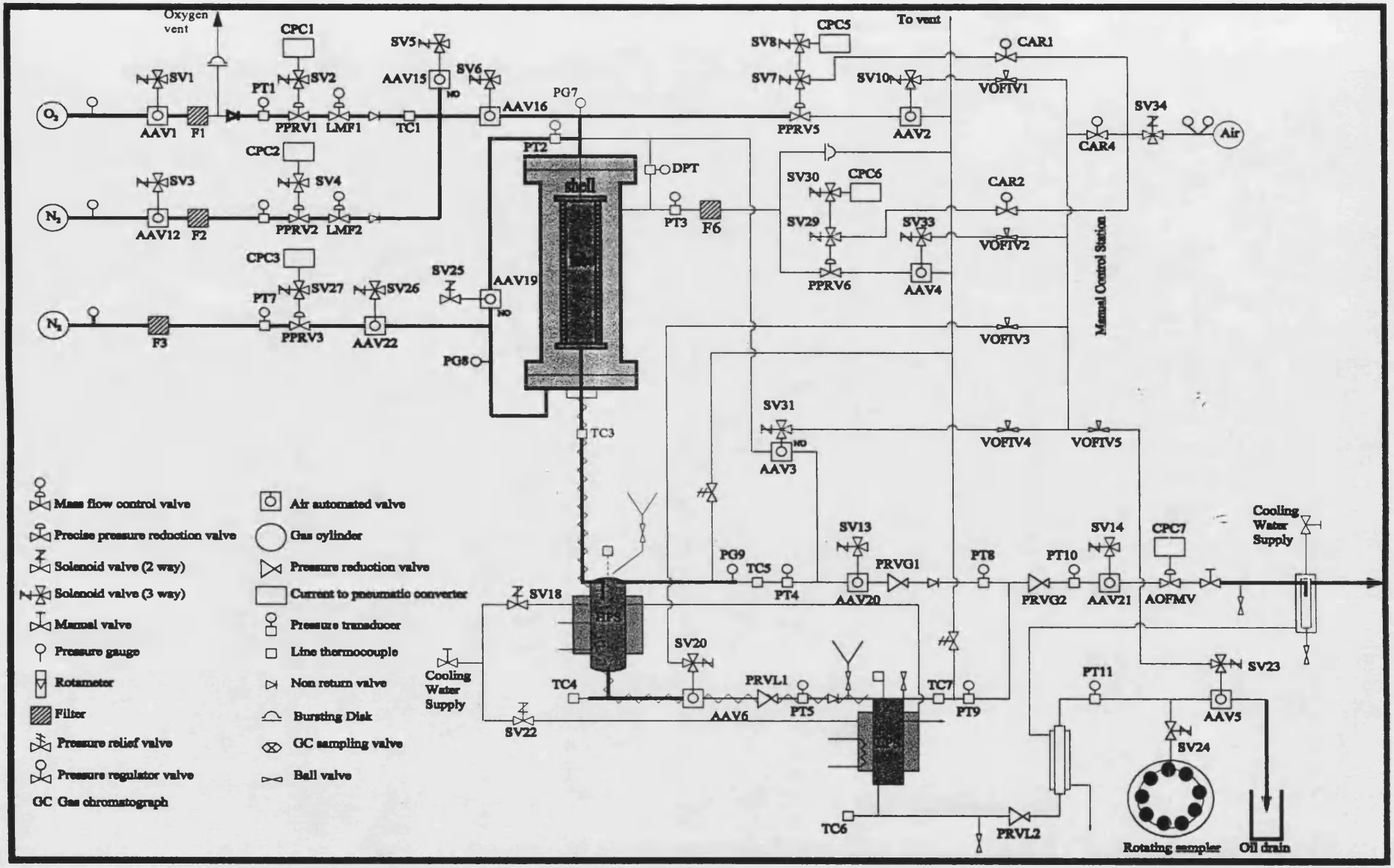
Fig-2 Schematic Diagram of the High Pressure Air Injection System Hardware Interaction (Electrical and Data Acquisition System)

Table-1 Items of Equipment in Fig-1

Safety Data Sheets of Substances Described in Section 2

Safety Certificates of the Pressure Equipment

cont...



Flowsheet of the high pressure ISC tube system

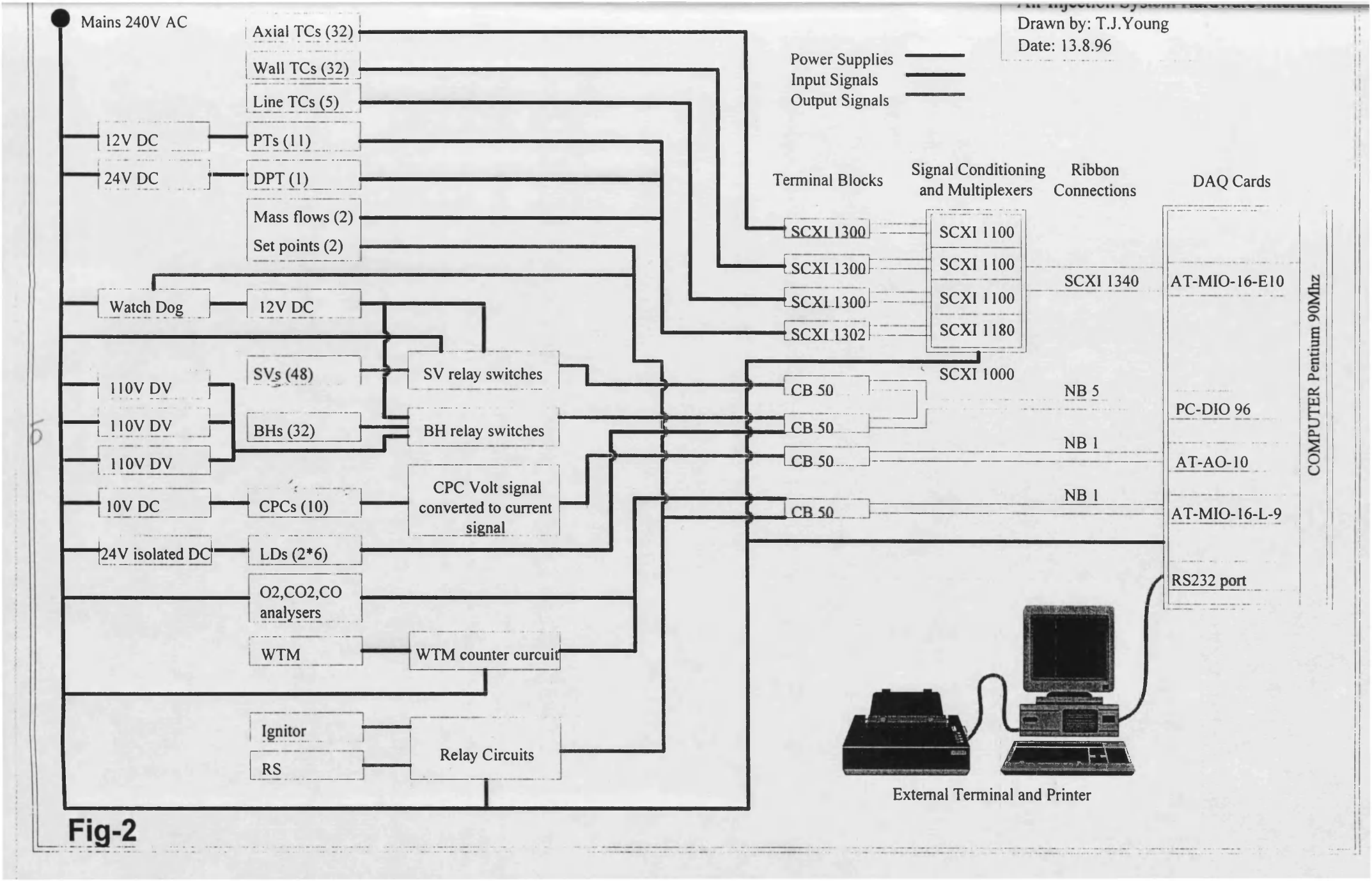

Drawn by: T.J.Young
Date: 13.8.96
Power Supplies
Input Signals
Output Signals
Mains 240V AC
Axial TCs (32)
Wall TCs (32)
Line TCs (5)
12V DC
PTs (11)
24V DC
DPT (1)
Mass flows (2)
Set points (2)
Watch Dog
12V DC
SVs (48)
110V DV
110V DV
BHs (32)
110V DV
10V DC
CPCs (10)
24V isolated DC
LDs (2*6)
O2,CO2,CO analysers
WTM
Ignitor
RS
SV relay switches
BH relay switches
CPC Volt signal converted to current signal
WTM counter curcuit
Relay Circuits
Terminal Blocks
Signal Conditioning and Multiplexers
Ribbon Connections
DAQ Cards
SCXI 1300
SCXI 1300
SCXI 1300
SCXI 1302
SCXI 1100
SCXI 1100
SCXI 1100
SCXI 1180
SCXI 1340
SCXI 1000
CB 50
CB 50
CB 50
CB 50
NB 5
NB 1
NB 1
AT-MIO-16-E10
PC-DIO 96
AT-AO-10
AT-MIO-16-L-9
RS232 port
COMPUTER Pentium 90Mhz
External Terminal and Printer

Fig-2

Table-1 Items of Equipment in Fig-1

Items	Description	Supplier
Standard Items:		
O_2	230 bar O_2 cylinder (w)	BOC
N_2	200 bar N_2 cylinder (n)	BOC
Air	Air compressor	Clarke International
CV1-CV5	No return valves	Swagelok
BV1-BV12	Ball valves	Swagelok
F1-F5	Filters	Swagelok
AAV1-AAV31	Air Automated Valves	Swagelok
PT1-PT11	Pressure Transducers	RDP Elec. Ltd
PG1-PG8	Pressure gauge	Budenberg Co Ltd.
DPT	Differential pressure transducer	Rosemount Eng. Co Ltd.
TC1-TC4	Mineral insulated on-line thermocouple	TC Ltd.
SV1-SV34	2/3 way solenoid valve, 240V AC	Asco (UK)
PPRV1-PPRV	Precise pressure reduction valve	Tescom Co.
PRVL1-PRVL2	Pressure reduction valve (liquid)	Tescom Co.
PRVG1-PRVG2	Pressure reduction valve (gas)	Tescom Co.]
LMF1-LMF2	Mass flow control valve	Brooks Instruments
CPC1-CPC7	Current to pneumatic converter	Smith-Watson Ltd.
AOFMV	Air operated fine metering valve	High Pressure Equip. Co.
CAR1-CAR4	Pressure regulator valve	Tescom Co.
RV1	Pressure relief valve	Swagelok
RS	Rotameter (gas sampling valve)	Valco Valves
Non-Standard Items		
CT	Combustion tube	Hodges Pain & Co.
Shell	Pressure shell	Hodages Pain & Co.
BH	Band heaters	Watlow Electric Mfg Co.
TW	Thermowell with 32 thermocouples	H & B Sensors Ltd.

cont...

IG	Ignitor	Watlow Electric Mfg Co.
HPS	High pressure separator	Hodges Pain & Co.
LPS	Low pressure separator	Univ. workshop
RS	Rotating sample table	Univ. workshop
LD1-LD2	Level detector	IOR Group Lab
BD1-BD3	Bursting disks	Marston Palmer Ltd.
Cooling water supply	Manual valve control	Water Tap
Oil drain	Oil Drainage vessel	IOR Group Lab
KOV	Knock out vessel	
Manual Control Station	Manual Control Panel in observation area	IOR Group Lab

cont...

Product Petroleum spirit 80–100 degrees C

Hazard Class 3 * UN No 1271 CAS No 8032-32-4

BDH (Product Codes 10180–10186–29815

PHYSICAL DATA

Description Colourless liquid petrol–like odour

M Pt(deg C) n a B Pt(deg C) n a Specific Gravity 0.69

Solubility in water Immiscible or insoluble

Vapour pressure n a mmHg at Deg.C
Vapour density 3 (air = 1)

FIRE AND EXPLOSION HAZARD Extremely flammable

Vapour air mixture explosive

Flash point(deg C) –2*
Explosive limits (%): lower 1 upper 8
Auto–ignition temperature(deg C) n a

Firefighting measures Foam, dry powder, carbon dioxide or vaporising liquids

HEALTH HAZARD The vapour may irritate the respiratory system and in high concentration, have a narcotic effect. Harmful by ingestion and skin contact. Extremely irritating to eyes

Toxicity data no data

Carcinogenicity No evidence of carcinogenic properties
Mutagenicity/Teratogenicity No evidence of mutagenic or teratogenic effects
Exposure limits OES.mg/m3 1000 (Long–term, 8 hour TWA)

FIRST AID

Eyes Irrigate thoroughly with water for at least 10 minutes. OBTAIN MEDICAL ATTENTION
Lungs Remove from exposure, rest and keep warm. In severe cases obtain medical attention
Skin Wash off skin thoroughly with water. Remove contaminated clothing and wash before re–use. In severe cases, OBTAIN MEDICAL ATTENTION
Mouth Wash out mouth thoroughly with water and give plenty of water to drink OBTAIN MEDICAL ATTENTION

Stability Stable

Reaction None with water

Other known hazards

Can react with oxidising materials

Avoid contact with Water (no) Acids (no) Bases (no)
Oxidisers (yes) Combustibles (no)

SPILLAGE DISPOSAL

Precautions Shut off all sources of ignition
Inform others to keep at a safe distance
Wear appropriate protective clothing

Absorb on an inert absorbent, transfer to container and arrange removal by disposal company. Wash site of spillage thoroughly with water and detergent

For large spillages liquids should be contained with sand or earth and both liquids and solids transferred to salvage containers. Any residues should be treated as for small spillages
If material has entered surface drains it may be necessary to inform local authorities, including fire services if flammable

PROTECTIVE MEASURES as appropriate to quantity handled

Respirator Self–contained breathing apparatus
Ventilation Fume–cupboard, flameproof
Gloves High grade PVC
Eye protection Goggles or face shield
Other measures Plastic apron, sleeves, boots–if handling large quantities

STORAGE AND HANDLING

Special requirements
As required by the Petroleum Act 1928 and the Highly Flammable Liquids and Liquefied Petroleum Gases Regulations 1972. In accordance with HSE guidance note CS17

HEALTH AND SAFETY INFORMATION

Product Toluene

Hazard Class 3.2 UN No 1294 CAS No 108–88–3

BDH Product Codes 10284–14627–15221–15295–15335–30452
30454–45109–71795–71980

PHYSICAL DATA

Description Colourless liquid benzene–like odour

M Pt(deg C) –95 B Pt(deg C) 111 Specific Gravity 0.86

Solubility in water Practically insoluble

Vapour pressure 36.7 mmHg at 30 Deg.C
Vapour density 3.14 (air = 1)

FIRE AND EXPLOSION HAZARD Highly flammable

Vapour air mixture explosive

Flash point(deg C) 7
Explosive limits (%) lower 1.4 upper 7
Auto–ignition temperature(deg C) 535

Firefighting measures Foam, dry powder, carbon dioxide or vaporising liquids

HEALTH HAZARD Inhalation may cause dizziness, headache, nausea and mental confusion. Vapour irritating to eyes and mucous membranes. Harmful by ingestion and skin contact. If benzene is present as an impurity, prolonged use may cause blood disease. Prolonged skin contact may cause dermatitis

Toxicity data LD50 5000 mg kg oral, rat

Carcinogenicity No evidence of carcinogenic properties
Mutagenicity/Teratogenicity No evidence of mutagenic or teratogenic effects
Exposure limits OES.mg/m3 375 (Long–term, 8 hour TWA)

FIRST AID

Eyes Irrigate thoroughly with water for at least 10 minutes. OBTAIN MEDICAL ATTENTION.
Lungs Remove from exposure, rest and keep warm. In severe cases, or if exposure has been great, OBTAIN MEDICAL ATTENTION
Skin Drench the skin thoroughly with water. Remove contaminated clothing and wash before re–use. Unless contact has been slight, OBTAIN MEDICAL ATTENTION.
Mouth Wash out mouth thoroughly with water and give plenty of water to drink OBTAIN MEDICAL ATTENTION

REACTIVE HAZARDS

Stability Stable

Reaction None with water

Other known hazards

Reacts violently with boron trifluoride at –80C. Can explode in contact with N2O4. Reacts vigorously with uranium hexafluoride. Nitration of toluene should be carefully controlled

Avoid contact with: Water (no) Acids (no) Bases (no)
Oxidisers (yes) Combustibles (no)

SPILLAGE DISPOSAL

Precautions Shut off all sources of ignition
Inform others to keep at a safe distance
Wear appropriate protective clothing

Absorb on an inert absorbent, transfer to container and arrange removal by disposal company. Wash site of spillage thoroughly with water and detergent.

For large spillages liquids should be contained with sand or earth and both liquids and solids transferred to salvage containers. Any residues should be treated as for small spillages
If material has entered surface drains it may be necessary to inform local authorities, including fire services if flammable.

PROTECTIVE MEASURES as appropriate to quantity handled

Respirator Self–contained breathing apparatus
Ventilation Fume–cupboard, flameproof
Gloves Nitrile
Eye protection Goggles or face shield
Other measures Plastic apron, sleeves, boots–if handling large quantities

STORAGE AND HANDLING

Special requirements
As required by the Petroleum Act 1928 and the Highly Flammable Liquids and Liquefied Petroleum Gases Regulations 1972. Take precautionary measures against static discharges.

HEALTH AND SAFETY INFORMATION

BDH

Product 1,1,1-trichloropropane
methyl dichloroethane

Hazard Class 6.1 UN No 2831 CAS No 71-55-6

BDH Product Codes 10347-30436-30704-45114-71570

PHYSICAL DATA

Description Colourless liquid, chloroform-like odour

M Pt(deg C) -32 **B Pt(deg C)** 74 **Specific Gravity** 1.34

Solubility in water Slightly soluble

Vapour pressure 100 mmHg at 20 Deg.C
Vapour density 4.54 (air = 1)

FIRE AND EXPLOSION HAZARD May evolve toxic fumes in fire

Flash point(deg C) n.a
Explosive limits (%) lower n.a upper
Auto-ignition temperature(deg C) n.a

Fire fighting measures Not applicable

HEALTH HAZARD Harmful by ingestion and inhalation. Prolonged exposure may cause liver and kidney damage. Degreases. Irritating to skin and eyes. May cause damage if splashed in eyes. Vapour is narcotic in high concentrations

Toxicity data LD50 10300 mg/kg oral rat; LC50 96 mg/l inh rat

Carcinogenicity Should be treated as a suspected carcinogen
Mutagenicity/Teratogenicity Evidence of mutagenic effects
Exposure limits MEL mg/m3 1900 (Long-term, 8 hour TWA)

FIRST AID

Eyes Irrigate thoroughly with water for at least 10 minutes. OBTAIN MEDICAL ATTENTION.

Lungs Remove from exposure, rest and keep warm. In severe cases obtain medical attention.

Skin Wash off skin thoroughly with water. Remove contaminated clothing and wash before re-use. In severe cases, OBTAIN MEDICAL ATTENTION.

Mouth Wash out mouth thoroughly with water and give plenty of water to drink. OBTAIN MEDICAL ATTENTION

REACTIVE HAZARDS

Stability Stable

Reaction Slowly liberates hydrochloric acid with water

Other known hazards

Explodes if heated in oxygen under pressure. Can react dangerously with nitrogen dioxide and with aluminium, potassium, magnesium and potassium sodium alloy

Avoid contact with: Water (no) **Acids** (no) **Bases** (no)
Oxidisers (yes) **Combustibles** (no)

SPILLAGE DISPOSAL

Precautions Wear appropriate protective clothing.
Inform others to keep at a safe distance.

Absorb on an inert absorbent, transfer to container and arrange removal by disposal company. Wash site of spillage thoroughly with water and detergent.

For large spillages liquids should be contained with sand or earth and both liquids and solids transferred to salvage containers. Any residues should be treated as for small spillages.
If material has entered surface drains it may be necessary to inform local authorities, including fire services if flammable.

PROTECTIVE MEASURES as appropriate to quantity handled

Respirator Self-contained breathing apparatus
Ventilation Fume-cupboard
Gloves Nitrile
Eye protection Goggles or face shield
Other measures Plastic apron, sleeves, boots-if handling large quantities

STORAGE AND HANDLING

Special requirements
Keep well sealed and protected from moisture

CHINA CLAYS

Labelling, Storage, Handling and Health and Safety Information

ECC International Ltd
John Keay House, St Austell,
Cornwall, England PL25 4DJ
Telephone: (0726) 74482
Telex: 45526 ECCSAU G
Fax: (0726) 623019

ECCI china clays are refined from naturally occurring materials and consist mainly of kaolinite with small quantities of mica and feldspar and a trace of quartz. No other form of free crystalline silica (e.g., cristobalite or tridymite) has been detected by x-ray powder diffractometry. Kaolinite is an alumino-silicate with the composition $Al_2Si_2O_5(OH)_4$.

Classification, Packaging and Labelling of Dangerous Substances Regulations 1984
Non dangerous substance according to the above regulations and does not contain any dangerous ingredient in excepted quantities according to Schedule 5 of these regulations.

Supplied as powder or lump in bulk, paper sacks and Intermediate Bulk Containers. Also supplied as slurry form in bulk.

Handling and Dust Creation
Depending on the form of china clay supplied, i.e., lump or powder and the method of handling, respirable dust may be created. The Health and Safety Executive publish a Guidance Note, EH 40, Occupational Exposure Limits, which forms part of the Control of Substances Hazardous to Health (COSHH) Regulations 1988. In the absence of a specific exposure limit for a particular dust, personal exposure should be kept below 10 $mg.m^{-3}$ 8-hour TWA total inhalable dust and 5 $mg.m^{-3}$ 8-hour TWA respirable dust. Where dusts contain components which have their own assigned occupational exposure limits all the relevant limits should be complied with. The Guidance Note EH 40 is revised and reprinted annually. Care should be taken to ensure that the latest issue is being consulted.

Skin Contact
Inert material. Normally no effect. Could cause dryness of skin on prolonged contact. Should be removed by washing with soap and water.

Eye Contact
Inert material. Normally no effect. Foreign bodies should be washed out with plenty of clean water. Seek medical aid if pain is experienced.

Ingestion
Non toxic. Non corrosive.

Fire and Explosion Risk
None.

Spillages
Avoid creating dust and preferably collect by vacuum cleaning or hose away with plenty of water.

Wet clay on floor surface can be a slipping hazard.

Disposal
Dispose of as a non toxic waste.

Storage
Unlimited shelf life.

EINECS/CAS Number

China clay does not appear in EINECS as an individual entry but is classified as "Naturally Occurring Substance" with the EINECS number: 3101276. Kaolin (China clay) is listed in the CAS registry with the number 1332-58-7.

The information contained in this Health and Safety Information Bulletin supersedes all previous such bulletins and is based on the company's current knowledge at 1st March 1990. If at any time the company becomes aware of any fact which indicates that this information is inaccurate in any material respect, a replacement bulletin covering the necessary amendments will be issued.

REF: CHCL/3/90

THE QUEEN'S AWARD FOR EXPORT ACHIEVEMENT
To ECC International (Sales) Ltd

Subject to the Conditions of Sale set out overleaf

Company No. 269255
Registered in England and Wales
Registered Office: 1015 Arlington Business Park, Theale, Reading RG7 4SA

MORGAN

Form No: MR F32
Issue No: 2
Issue Date: April'89

HEALTH AND SAFETY PRODUCT DATA SHEET

Manufacturer/Supplier: MORGANITE THERMAL CERAMICS LIMITED

Liverpool Road
Neston
South Wirral L64 3RE

Tel: 051-336-3911
Tlx: 627174 Hytem G
Fax: 051-336-7868

PRODUCT NAME	KAOWOOL CERAMIC FIBRE BLANKET
EMERGENCY CONTACT	MR. K.H. JACKSON
General Description and Use	Blanket form of Ceramic Fibre used for Thermal Insulation.

Potential Health Hazard

May cause irritation to skin, eyes or via ingestion. There is some concern over fibrous dusts, since long term over exposure may cause tissue response in the lung. The fibres consist of a silicate glass which could transform on heating to cristobalite (a form of crystalline silica). Repeated inhalation of respirable free crystalline silica dust may cause delayed lung injury (silicosis). Since the removal of this product after use may result in the generation of dust, then suitable respiratory equipment for use with crystalline silica must be used and the recommended OEL for free crystalline silica adopted.

Storage and Handling	Keep Dry
Waste Disposal	Normal Land Fill
Action in Case of Spillage	Collect large pieces and vacuum up dust as necessary.
Fire Extinguishing Media	N/A
Advice on Label	Yes
Fire and Explosion Hazard	N/A
Flash Point °C (Method of Determination)	N/A

CONTENTS:- The percentage compositon of each constituent is stated by its chemical name and also states whether the percentage is by weight or volume

THIS INFORMATION TO BE RETAINED IN CONFIDENCE BY THE HEALTH AND SAFETY DEPARTMENT OF YOUR COMPANY.

Ceramic Fibre C.A.S. No. 65997-17-3

Amorphous Fibres of Composition

Alumina	30-50%
Silica	47-57%
Zirconia	0-20%

Ocupational Exposure Limits	MEL for man made mineral fibres 5 mg/m³. OEL for crystalline silica 0.15 mg/m³ total inhalable dust, 0.05 respirable dust.
Preventative Measures	Avoid generating respirable dust by rough handling Where dust generation cannot be avoided, use exhaust ventilation, or wear suitable respirators to maintain the respirable dust level below 5mg/m³
Personal Protective Equipment	Do not wear tight collars or cuffs which will increase skin irritation.
FIRST AID - Inhalation - Skin Contact - Eye Contact - Ingestion	 Remove from contact Wash skin with soap and water Irrigate eyes thoroughly
Miscellaneous Information (eg reaction with other materials thermal decomposition products)	

K.H. Jackson ..... Date: July 1989

for MORGANITE THERMAL CERAMICS LIMITED

CONSIGNEE WITH GOODS (PINK COPY) 2. CHIEF INSPECTOR - CONSIGNEE (GREEN COPY) 3. CONSIGNOR'S COPY (WHITE COPY) 006

HODGES PAIN & C

General & Mechanical Engineers · Welded Fabrications

Proprietors
M. E. PAIN
P. A. PAIN

Reg. Office
DAYS ROAD, ST. PHILIPS
BRISTOL, AVON, BS2 0QS
Telephone 0272 551027

CERTIFICATE OF CONFORMITY
B.S.I. Registration Nos. FM 432, FM 432/1, FM 432/2

CONSIGNED TO

University of Bath,
School of Chemical Engineering,
Claverton Down,
Bath, BA2 7AY.

DATE 22nd September 1989

CONTRACT No. ———

ORDER No. 344384

WORKS ORDER No. HP.3828

VENDORS APPROVAL No. ———

PRODUCT QUALIFICATION APPROVAL No. ———

ITEM	QUANTITY	PART No. DRG No.	DESCRIPTION	LOT IDENTIFICATION	CAST No. BATCH No.
1	1		Fabrication of Combustion Tube to Design 3	HPB.235/1 PT.No.242/A PT.No.243	
		NB. PT.No.242/A	Pressure Tested to 5000lbs/ins^2		
		PT.No.243	Pressure Tested to 50 lbs/ins^2		

CONDITION OF MATERIAL ON DESPATCH ———

FURTHER TREATMENTS TO MATERIAL ———

CONCESSION No. ———

TEST REPORT No. ———

Certified that the supplies/services detailed hereon have been inspected and tested in accordance with the conditions and requirements of the contract or purchase order and unless otherwise noted below, conform in all respects to the specification(s), drawings(s) relevant thereto.

Quicksets

D. PRDOSE

For and on behalf of
HODGES PAIN & CO

INSPECTION STAMP

HP

PRESSURE TEST RECORD.

PT No. 242-1

DATE TESTED 12-9-89

ORDER No. 344384

GKS ORDER No. H.P. 35828

QUANTITY	PART No. DEG. No.	DESCRIPTION
1	—	COMUSTION TUBE

TEST PRESSURE 5000 LBS/INS^2

TESTED BY W.E. Brigg

WITNESSED BY K.S. Thorne

PRESSURE TEST CURVE —

TEST APPROVED K.S. Thorne

CERT. ISSUED —

DATE TESTED 28-2-89

PT No. 208

ORDER No. 3441203

Works Order No. H.P. 4000

QUANTITY	PART No. DEG. No.	DESCRIPTION
1	✓	HIGH PRESSURE SEPARATOR

TEST PRESSURE 4785 LBS/IN²

TESTED BY J F Bigland

WITNESSED BY HP1

PRESSURE TEST CODE

TEST APPROVED HP11

CERT. ISSUED

HODGES PAIN & CO.
DAYS ROAD, ST. PHILIPS,
BRISTOL, AVON. BS2 0QS
Telephone: 0272 551027

Marston Palmer Limited

Wobaston Road, Fordhouses
Wolverhampton WV10 6QJ
England

Telephone Wolverhampton (0902) 397777
Telegrams & Telex 337782 MARSTN G
Fax 02-411 MARSTN
337183 MARSTN

IMI

Marston Palmer Ltd.
was previously
IMI Marston Ltd.

SAFETY SYSTEMS GROUP

SAFETY DISC TEST CERTIFICATE

ORDER NO. SD 009482/1

Customer THE UNIVERSITY OF BATH

Ref. AM 8652
Sheet 1 of 1
Date 20-12-85
No. of Certificates 1

Customer Ref 34443p

REQUIREMENTS

Number of items Discs 6 — Inspectors 1
Number of discs for test 2 — Material — Matl. C.STEEL
Type of Discs AM — Nom Bore 1 1/4 ins.
Disc material INCONEL — Ref. Our Dwg. No. 0880-8A (Iss 5) 1 1/4" NPT
Burst Pressure Kg/cm²g 270 Bar.g Kg Cm²g PSIg 150 °C

MATERIAL PRODUCED

Note:- This batch of discs has been made to a manufacturing range of + 0 % — 0 %

Rated Burst Pressure	Kg/cm²g 270	Bar. g	Kg Cm²g 3915	PSIg	450	°C
Rated Burst Pressure	Kg/cm²g 300	Bar. g	Kg Cm²g 4350	PSIg	20	°C
Burst tolerance + 5 %		Max.		PSIg		
— 5 %		Min.		PSIg		

TEST RESULTS

Test No.	PSIg	°C	Inspectors Stamp	Test No.	PSIg	°C	Inspectors Stamp
1	4200	20		11			
2	4150	20		12			
3				13			
4				14			
5				15			
6				16			
7				17			
8				18			
9				19			
10				20			

Special Remarks

Certified on behalf of Marston Palmer

Signature M W Smith Date 20-12-85

Certified on behalf of

Signature Date

20

ESSO PETROLEUM COMPANY LIMITED
PRODUCT HEALTH & SAFETY DATA

RODUCT IDENTIFICATION

DE NAME:
IUDE OIL

NUMBER:	8002-05-9
ONYM(S):	CRUDE OIL; ROCK OIL; SENECA OIL
AL FAMILY:	HYDROCARBON
ECULAR FORMULA:	MIXTURE
ECULAR WEIGHT:	ND
DUCT CODE:	P 0001-0099 HIERARCHY: 030.000

RODUCT HAZARD SUMMARY

LTH

DANGER!
VAPORS MAY BE HARMFUL
POSSIBLE ASPIRATION HAZARD
MAY BE IRRITATING TO THE SKIN, EYES AND RESPIRATORY TRACT
MAY RELEASE TOXIC HYDROGEN SULFIDE VAPORS
SKIN CANCER HAZARD BASED ON TESTS WITH LABORATORY ANIMALS

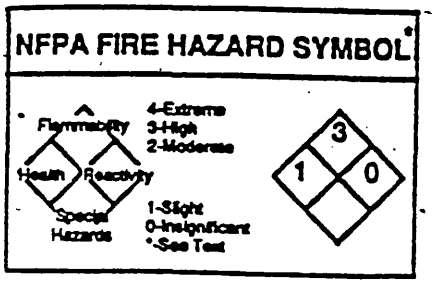
MMABILITY

DANGER!
EXTREMELY FLAMMABLE LIQUID
VAPORS MAY EXPLODE

.VITY

STABLE

NFPA FIRE HAZARD SYMBOL



ht © 1980, National Fire Protection Assoc., MA 02269.
rinted material is not the complete and official position of the NFPA on the referenced subject, which is represented
the standard in its entirety.

PRODUCT HEALTH HAZARD INFORMATION

ESTION:
spiration into lungs may cause pneumonitis. May cause gastrointestinal disturbances. ymptoms may include irritation, nausea, vomiting and diarrhea.

IN:
epeated or prolonged contact may result in defatting, oil acne, redness, itching, nflammation, cracking and possible secondary infection. Absorption from prolonged or assive skin contact may cause poisoning. May cause allergic reactions in some ndividuals.

E:
irect contact may cause irritation. Exposure to vapors, fumes or mists may cause rritation.

HALATION:
ay cause respiratory tract irritation. Exposure to high concentrations of dense oil ists may lead to oil pneumonia. May release toxic hydrogen sulfide vapors and cause armful central nervous system effects. Effects may include excitation, euphoria, eadache, dizziness, drowsiness, blurred vision, fatigue, tremors, convulsions, loss of consciousness, coma, respiratory arrest and death.

ECIAL TOXIC EFFECTS:
Crude oils contain some polynuclear aromatic hydrocarbons which have been shown to be carcinogenic after prolonged or repeated skin contact in laboratory animals. Some crude oils have been shown to cause skin cancer in laboratory animals and crude oil fractions have been positive in mutagenic test systems. Toxic hydrogen sulfide vapors may be released from crude oils. In addition, the presence of various heavy metals in crude oil may pose a bioaccumulation potential which could lead to systemic toxicity by repeated or prolonged inhalation, ingestion or skin absorption.

IARC has determined that there is limited evidence for the carcinogenicity of crude oil i experimental animals and inadequate evidence for the carcinogenicity of crude oil in humans.

NOTE: This product has not been tested as a whole for all potential health effects. It may have other health hazards related to its components. See "Ingredient/Health Hazards" for additional information.

FIRST AID

NGESTION:
DO NOT INDUCE VOMITING BECAUSE OF DANGER OF ASPIRATING LIQUID INTO LUNGS. If spontanec vomiting occurs, monitor for breathing difficulty. Get immediate medical attention.

KIN CONTACT:
Remove contaminated clothing immediately. Wash area of contact thoroughly with soap and water. Do not use petroleum-based solvents to remove oil from skin. Get medical attention if irritation persists. Launder clothing before reuse. Discard contaminated leather goods.

YE CONTACT:
Flush immediately with large amounts of water for at least 15 minutes. Eyelids should b held away from the eyeball to ensure thorough rinsing. Get medical attention if

ritation persists.

ALATION:
move affected person from source of exposure. If not breathing, ensure open airway and
stitute cardiopulmonary resuscitation (CPR). If breathing is difficult, administer
gen if available. Get immediate medical attention.

NOTES TO PHYSICIAN

spiration of petroleum hydrocarbons may cause severe pneumonitis (oil pneumonia).
miting should not be induced. In unconscious victims, use of an endotracheal tube should
considered if gastric lavage is undertaken.

PERSONAL PROTECTION INFORMATION

E PROTECTION:
ar safety glasses or chemical goggles to prevent eye contact with dust. Have eye
shing facilities readily available where eye contact can occur. Do not wear contact
nses when working with this substance.

N PROTECTION:
ar impervious gloves and protective clothing to prevent skin contact. Use good personal
ene. Wear regularly cleaned work clothing. Showering and changing into street
thing after work is desirable.

PIRATORY PROTECTION:
ntilation may be used to reduce airborne concentrations. If ventilation cannot reduce
irborne concentrations below acceptable limits, appropriate respiratory protection should
used. Use NIOSH or MSHA approved respiratory protective equipment when airborne
posure limits are exceeded. NIOSH/MSHA approved respiratory protective equipment must
available for non-routine and emergency use.

PHYSICAL PROPERTIES

LING POINT: -17.8 - 537.8 C (0-1000 F)
CIFIC GRAVITY: 0.74 - 1.03
LTING POINT: NA
OLATILE: VARIES
OR PRESSURE: 0.60 - 10.00 LBS. (REID)
PORATION RATE (WATER=1): ND
DENSITY (AIR=1): > 1.0
OSITY: VARIES
OLUBILITY IN WATER: NEGLIGIBLE
R POINT: VARIES
ND
EARANCE/ODOR: DARK BROWN/BLACK OIL WITH HYDROCARBON/HYDROGEN SULFIDE ODOR.

No Data
Not Applicable

RE AND EXPLOSION DATA

ASH POINT: -42.80 - 93.30 C (-45 - >200 F) NOTE: DEPENDENT ON CRUDE OIL TYPE
TOIGNITION TEMPERATURE: ND
AMMABILITY LIMITS IN AIR (% BY VOL.) LOWER: ND UPPER: ND

SIC FIREFIGHTING PROCEDURES:
se dry chemical, foam or carbon dioxide to extinguish fire. Water may be ineffective but hould be used to cool fire-exposed containers, structures and to protect personnal. If ak or spill has not ignited, ventilate area and use water spray to disperse gas or vapor id to protect personnal attempting to stop a leak. Use water to flush spills away from ources of ignition. Do not flush down public sewers.

JSUAL FIRE AND EXPLOSION HAZARDS:
ngerous when exposed to heat or flame. Vapors form flammable or explosive mixtures with ir at room temperature. Vapor or gas may spread to distant ignition sources and flash ck. Vapors may concentrate in confined areas. Containers may explode in heat of fire. noff to sewer may cause fire or explosion hazard. Irritating or toxic substances may be itted upon thermal decomposition. Exposed firefighters must wear MSHA/NIOSH approved lf-contained breathing apparatus with full face mask and full protective equipment.

EACTIVITY DATA

BILITY/INCOMPATIBILTY:
able under normal conditions of use. Avoid contact with strong oxidizers.

ARDOUS REACTIONS/DECOMPOSITION PRODUCTS:
ritating and toxic fumes may be emitted upon decomposition. Combustion may produce CO, 2 and reactive hydrocarbons. May also produce SOx and hydrogen sulfide. Hydrogen lfide is corrosive to many materials when moist.

NVIRONMENTAL INFORMATION

L OR RELEASE TO THE ENVIRONMENT:
your facility or operation has an "Oil or Hazardous Substance Contingency an", activate its procedures.

Take immediate steps to stop and contain the spill. Caution should be exercised regarding personnal safety and exposure to the spilled material.

For technical advice and assistance related to chemicals, contact CHEMTREC (800/424-9300) and your local fire department.

Notify the National Response Center, if required.

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rgency Action:
p unnecessary people away. Stay upwind; keep out of low areas. Isolate hazard area deny entry. (Also see Personal Protection Information section.) Isolate for 1/2 mile all directions if tank or tankcar is involved in fire.

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or Leak Procedure:
flares, smoking or flames in hazard area. Stop leak if you can do it without risk. ll Spills: Take up with sand or other noncombustible absorbent material or other bent known to be compatible, then flush area with water. Large Spills: Dike far ahead spill for later disposal.

: Sampling, Transferring and shipping personnel should use extreme caution when ning a sealed container or entering confined areas of stored crude oil. Proper piratory equipment should be used when opening and entering such containers due to the bability of hydrogen sulfide vapors being released.

ANSPORTATION REQUIREMENTS

HAZARD CLASS (49 CFR 172.101):	FLAMMABLE OR COMBUSTIBE LIQUID
PROPER SHIPPING NAME (49 CFR 172.101):	CRUDE OIL, PETROLEUM
LABELS REQUIRED (49 CFR 172.101):	FLAMMABLE LIQUID OR NONE

PLACARDS REQUIRED: FLAMMABLE OR COMBUSTIBLE

OF LADING DESCRIPTION: CRUDE OIL, PETROLEUM FLAMMABLE LIQUID, UN 1267 OR CRUDE OIL, PETROLEUM COMBUSTIBLE LIQUID UN 1267

A CODE: UN 1267

GREDIENTS/HEALTH HAZARD INFORMATION

COMPONENT	CAS NO.	%	EXPOSURE LIMITS - REFERENCE
oleum Crude Oil- A complex ination of hydrocarbons. onsists predominantly of ffins, cyclic paraffins, lc aromatic hydrocarbons ng carbon numbers predomi- ly greater than C1. May contain small amounts of	8002-05-9	99-100	5 mg/M3 TLV; 10 mg/M3 STEL (ACGIH 1989-90) for mineral oil mists 5 mg/M3 PEL (OSHA) for mineral oil mists

lth hazards: [illegible] rough the skin. Dog oral LDLo = 2,000 mg/kg. Rat LC50 = 10,000 ppm/7 urs. Aspiration hazard. Moderately irritating to the skin. May cause llergic reactions in some individuals. Severely irritating to the eye. ute benzene poisoning causes central nervous system depression. Benzene is rcinogenic to laboratory animals when given by intubation or by inhalation. ronic exposure affects the hematopoietic system causing blood disorders cluding anemia and pancytopenia. There is an association between cupational exposure to benzene and human leukemia. This association is sed on limited information and is currently unresolved. Mutagenic and utogenic in mammalian and non-mammalian test systems. Reproductive ficant only at doses that are maternally toxic, based on tests with imals. Carcinogenic determinations: IARC--Human positive and animal spected carcinogen; NTP--Known carcinogen; ACGIH--Suspected carcinogen.

ogen Sulfide	7783-06-4	Trace	10 ppm (14 mg/M3) TLV; 15 ppm (21 mg/M3) STEL (ACGIH 1989-90) 10 ppm (14 mg/M3) PEL; 15 ppm (21 mg/M3) STEL; 20 ppm CEIL; 50 ppm 10-minute PEAK (OSHA) 10 ppm 10-minute CEIL (NIOSH)

No Data
Not Applicable

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AIR INJECTION INTO WATERFLOODED LIGHT OIL RESERVOIRS

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Analysis based on the phase behaviour of selected light oil pseudo-components have been used to simulate combustion tube experiments. 1-D comparative reservoir simulation studies have been conducted to evaluate the displacement characteristics of air injection/in situ combustion processes in high pressure volatile-oil reservoirs. The numerical simulations have been performed using Computer Modelling Group's fully implicit thermal reservoir simulator 'STARS'. Combustion tube experiments have been designed to determine the nature of the propagating combustion front and the resulting dynamic reaction process behaviour typical of light oil under North Sea reservoir conditions.

INTRODUCTION

Improved oil recovery (IOR) is the term used to describe the rapidly advancing technology aimed at recovering the 60% or more of oil left behind by conventional production methods. Air injection is a promising IOR technique to generate suitable gases insitu (low temperature oxidation process), such as nitrogen for GSGI, WAG, etc, and also as a more advanced Enhanced Oil Recovery (EOR) process with considerable potential to recover both heavy and light crude oils(1,2). This requires detailed understanding of the interacting subprocesses involved: distillation, steamflood, CO_2 drive, etc, and most importantly, the precise fuel mechanism-combustion path. The high temperature oxidation or insitu combustion process involves the propagation of a burning front in a reservoir by injecting air down a well and burning a small proportion of the oil in place(3). The combustion front not only sweeps out the reservoir but can also produce significant upgrading of the oil due to thermal cracking(4).

It is generally thought that a light oil is fuel deficient, i.e. lacking in heavy ends needed for fuel laydown. This is probably true in certain cases if viewed simply from its low pressure characteristics. However, at the high pressures and temperatures prevailing in North Sea reservoirs the oil can auto-ignite. This auto-ignition phenomenon can cause a localised combustion state in the reservoir, so that the combustion front 'jumps' or 'skips' to the next fuel location downstream when available fuel is exhausted or becomes insufficient to sustain combustion. In this way an overall stable combustion front will result.

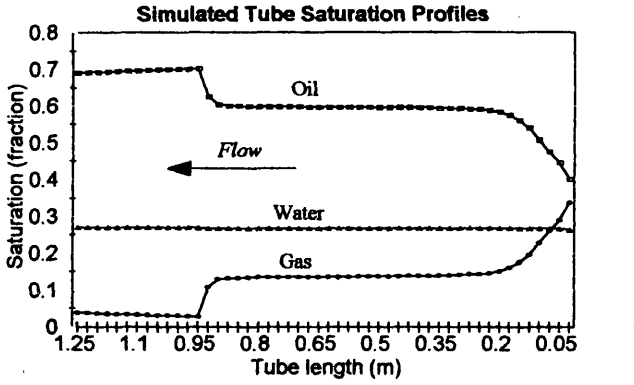
One of the principal items of equipment used to investigate this behaviour is the combustion tube reactor, the importance of which has recently been noted by Farouq Ali(5). This tube is packed with oil and sand to simulate a 1-D section in a reservoir. The thin wall reduces axial heat conduction and allows heaters along the length of the tube to counteract the effects of radial heat loss. Air is injected at the top end of the vertically inclined tube, and the sand pack ignited. The produced oil and gases are collected and analysed at the other end.

The object of this study is to examine the feasibility of air injection processes in North Sea type, high pressure, volatile-oil reservoirs and investigate the sensitivity of oil recovery performance to various parameters especially the method of combustion front propagation which to controls the process efficiency.

EQUIPMENT

A basic diagram of the apparatus can be seen in Figure 1 and consists of four main sections: i) the oxygen/nitrogen injection, ii) the combustion tube reactor, iii) separation of the produced oil and gases and iv) the sampling and analysis of these. A brief description of this is given below.

In one series of simulations carried out with a very low permeability sand pack it was observed that increasing air injection rates decreased the temperature of the combustion front. The low temperature front achieves more effective oil displacement and better flue gas stripping as the injection rate increases, which in turn reduces the amount of fuel available for combustion. This behaviour is different to that observed by other workers who used higher permeability sand packs. In this case, an increase in air injection rate increases the combustion front temperature (7). This behaviour is very important for controlling the combustion front temperature. Thus, there may be a level of reservoir permeability where the control of the combustion front temperature is critical, and may give rise to a different air injection strategy.



Saturation Profiles Figure (2)

Another important aspect of control involves establishing the method of combustion front propagation. It has been mentioned that in a light oil reservoir at high pressure this can occur due to an auto-ignition process. This 'skipping' or 'jumping' process of auto ignition is likely to take place over distances comparable to, or less than, the width of the combustion front (~3cm). Unfortunately axial temperature measurement along the combustion tube take place every 5cm and therefore this skipping process may not be observed. However, if the temperature at one point in the tube is recorded at a high rate while the combustion front passes, then a steep increase in gradient (compared to that normally expected due to the combustion of deposited coke) should indicate a zone of auto-ignition. Because the process is effectively random it may be difficult to measure. However by carrying out this test at each axial thermocouple position in the tube as the combustion front moves along it, the comparison of these individual graphs over a number runs may be conclusive.

Yannimaras et al (7) noticed a different type of skipping in his experiments with light oil. In this case a high temperature combustion front could not be maintained because of lower oil saturations due to increased displacement. However, after a period of cooler combustion front propagation, sufficient fuel again became available for further high temperature combustion to take place. In this way the Combustion front appears to 'skip'. This took place over a distance of about 0.7m.

CONCLUDING REMARKS

1. The STARS numerical simulator has been used to design two series of combustion tube experiments. One set uses 'Clair' crude (W. Shetlands), a medium heavy oil, and the other uses 'Forties' as a light crude oil. The combustion tube tests will focus on the effect of air flux at high pressures, up to 200bar, and look closely at determining the exact method of combustion front propagation.
2. Further simulations are to be performed on the effect of permeability in light oil high pressure reservoirs.
3. History matching of the combustion tube tests will be used to construct a 2D model for reservoir 'scoping' trials screening the IOR potential of air injection.

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